APPENDIX A: Analysis of Ignition Sources

Potential ignition sources were evaluated based on physical evidence, analysis of changes, worker interviews, and historical information. The relative likelihood of each ignition source was judged on a qualitative scale based on factors that either supported or reduced the likelihood. The table below contains the results of the team's analysis.

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Electrical Equipment Arc/Sparking	Low	Booster Room 2 differed from Booster Room 1 in that electrical motors instead of hydraulic systems were used to drive the mixing blades. If the electric systems were not installed properly, grounded, and maintained, then an electrical arc, spark, or fire could supply the stimulus to ignite or detonate the raw materials and the boosters that were present in Booster Room 2. Forklift operations in the booster room could also supply electrical sparks.	Explosion-proof motors, wiring, and lighting had been installed in Booster Room 2. The electrical panels and most of the wiring were located outside of the booster room. The electric motors for the mixing pots were supplied with a positive airflow around the motor housings which reduced the risk of dust and explosive material buildup near the motor windings.
Static Electricity	Low	The booster room floor had been painted with a non-conductive epoxy paint that would prevent the dissipation of static-charge buildup. The bristles of the brooms, used to sweep the floor area, were made of synthetic fibers that through friction with the floor could generate a static charge. The booster room also contained plastic buckets and dust pans that could form a static charge through friction with worker clothing and other materials. The workers frequently wore their own personal clothing under the company-supplied cotton coveralls. Friction between personal clothing with a high synthetic fiber content and the	Cleaning operations, which could be a source of static charge, would not be expected in Booster Room 2 at the time (7:54 AM) of the incident. *DoD Contractors' Safety Manual for Ammunition and Explosives* states "Humidification for preventing static electricity accumulations and subsequent discharges is usually effective if the relative humidity is above 60 percent." The relative humidity, reported by the weather service that morning, was over 80 percent in Reno. It was reported that PETN with a higher moisture content was brought to

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Static Electricity (continued)		cotton overalls could supply an ideal condition for formation of a static charge. Because of the cold outdoor temperature on the day of the incident, the workers wore their regular clothing under their coveralls. The pouring of dry explosives, especially PETN, and airflow friction from the ventilation system could generate hazardous levels of static electricity. During the interviews of Sierra employees, operators reported that static-charge buildup occurred during raw-material handling in the booster room. The problem appears to have been particularly severe while pouring dried PETN. At the time of the explosions, the pots could be at their operating temperature of 85°C, and although the relative humidity reported by the weather service was over 80 percent, the relative humidity near the operating areas of the pots could be well below 60 percent.	Booster Room 2 due to the higher heat capacity of the steam-heated mixing pots. The electric discharge energy required to detonate PETN increases with increasing water content. Cold ambient temperatures also increase the ignition energy required.
Mechanical Spark Caused by Nails When Pallet is Dragged Across Concrete	Low	Mechanically generated sparks could ignite dust and explosive raw material on the booster-room floor.	The raw explosive materials already had been staged in Booster Room 2 the previous day. The forklift was not in use. Ignition of dust on the booster-room floor is not likely to transition from deflagration to detonation.
Ferrous Metal Objects Impact, Generating a Spark	Moderate	The Comp-B that was used as a raw material sometimes contained foreign material. If the foreign object was composed of a ferrous material and was impacted by a hammer blow or mixer-blade, then a spark could have resulted and ignited the raw material.	Some employees visually inspect the Comp-B as it is opened.
Friction and Static when Dry PETN is Mixed	Moderate	PETN was sometimes added to the Pentolite mixing pot before molten TNT was present to remove any residual moisture. The presence of dry PETN increased the ignition sensitivity.	

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Friction when Pallet Slides Over Explosives on Floor	Improbable	Such mechanical action could supply sufficient energy for ignition.	The interviewed workers were aware of the potential dangers of bulk explosives or excessive manufacturing residue and waste on the pour-room floor. Good housekeeping practices were emphasized. Raw materials already had been staged in the booster rooms so no movement of pallets would be expected.
Forklift Strikes Explosives	Improbable	A forklift impact on containers of the raw material or the finished product could supply enough energy by spark, friction, or impact to trigger an ignition and/or detonation of the contacted material.	The forklift was located in the warehouse, and workers who might use it had not started work.
Striking Explosives with Metal Tools	Moderate	It was common practice to break up rejected boosters of Comp-B with both plastic and steel hammers. A review of U.S. Army incident summaries indicates that numerous past incidents were caused by the impact of hand tools on explosives containing TNT and RDX.	Only two boxes of rejected boosters had accumulated in Booster Room 2 since it went into operation. Rejected boosters were to be taken from Booster Room 2 to Booster Room 1 to be broken up and recycled. The explosion occurred in Booster Room 2.
Mixing Blade Impacts Hardened Explosives	High	If residual solid-base mix or Pentolite remained in the pot and the melt-pot mixing blade was engaged, impact forces on the explosives could ignite a large quantity (~50lbs.) of the base mix or Pentolite. Reportedly, about 50-100 lbs. of base mix had been left in pot 5 the preceding night. The crossover of personnel and melting techniques from the evening shift to the day shift increased the chance of operators not taking the proper sequence of steps to ensure a melt had formed before engaging the mixing blades. Because the operator in Booster Room 2 had previously worked on the second shift in Booster Room 1, he never had to inspect the pot in Booster Room 1 before turning on the mixer. An inspection of the pot was not needed in Booster Room 1	When asked, operators recognized that the pots should be inspected at the beginning of a shift to ensure that no solid material was present in the pot. Most operators, however, did not include this step in describing the melt/pour process. No startup checklist existed and a record to ensure that the inspection occurred was not maintained.

Potential Ignition Source	Relative Likelihood	Supporting Factors	Factors that Reduce Likelihood
Mixing Blade Impacts Hardened Explosives (continued)		because the heat would have been left on and the material still would have been melted from the previous shift. Because the two operators in Booster Room 2 had talked about the leftover base mix, the operator who left it may have assumed the other operator had used it.	
Tool or Pot Component Drops into the Pot	Low	Workers indicated that at times large pieces of Comp-B were broken up with hammers on top of, or even on the edge of, the opening into which the raw explosive materials were poured into the pot.	A component entering one of the large mixing pots is unlikely. The large mixing pots have no internal removable parts, and the penetrations through the lid around the shaft and breaker bars do not permit materials to enter the pot. Because of the heating capacity of the pots in Booster Room 2, there was less need to break down Comp-B clumps.
Foreign Object in the Explosives Struck by Mixing Blade	Low	Foreign materials were frequently found in the Comp-B. Comp-B and substitute materials were recovered from DoD munitions and would be expected to have foreign materials present from the demilitarization operations. Only cursory visual inspections of the Comp-B were used to eliminate foreign materials. The Comp-B was never screened on site to remove foreign objects. If a foreign object were to jam between the mixing blade and the pot wall, drag friction and pinching could readily provide the energy necessary to ignite or detonate the base mix.	There was an approximately one-inch clearance between the mixing blade and the tank wall. Any foreign objects that might strike the mixing blade and pot wall would need a size greater than about one inch. The tanks in Booster Room 2 were designed with a drain line that provided additional clearance below the mixing blade in the base of the pot. The mixing blade turned at a relatively low rotation rate, so the impact velocity on a foreign object present in the mix would be minimal.
Open Flame due to Lighters/Smoking	Low	Workers were not prohibited from bringing smoking materials into the change room in their regular clothes. Cigarettes and a lighter were found in a coat located in the debris near the change room.	The operator who was working in Booster Room 2 smoked little, if at all, and workers knew that they were only to smoke in the break room and could be fired if they were caught smoking anywhere else.
Chemical Reaction Between Explosive Types	Improbable	The Comp-B used to produce the boosters is demilitarized material. The explosive is purchased through a bid process delivered in bulk quantity "as is."	Explosives, including HMX, LX-14, Comp A-3, and Comp-H-6, had been melted and blended before without evidence of chemical reaction. An immediate

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
		Examination of the Comp-B currently in Sierra's inventory showed that, besides the material labeled as Comp-B, other military explosive compositions were included. Other demilitarized explosives present in the storage magazine included HMX, LX-14, Comp A-3, and Comp H-6. These explosive formulations were found in the same storage area of the magazine and often were observed on the same pallets as the Comp-B. All explosives were packaged in similar brown cardboard boxes that differed only in the attachment of a small label identifying the contents. The operators were not trained to recognize the difference in properties of the non-Comp-B explosives. Instead, they treated the non-Comp B explosives like Comp-B and added the other explosive formulations to the base mix as if the other compositions were actually Comp-B. Operators relied on process experience to limit the amount of some material, like HMX, that they would add to the mix because they observed that the material would not melt. Sierra did not test the explosives for chemical purity, nor was the material subjected to physical sensitivity tests, such as differential thermal analysis. The actual chemical purity and the behavior of different batches of raw material when heated was therefore unknown. Chemical incompatibility and the possibility of violent chemical reaction among the different explosive compositions cannot be ruled out, especially given the manufacturing process of heating, melting, and blending.	and violent chemical reaction without some early indication of reaction, like the emission of NOx vapors, is not considered a credible failure mode.

Potential Ignition Source	Relative Likelihood	Supporting Factors	Factors that Reduce Likelihood
Cross-Contamination Between Processes	Improbable	Other chemicals, incompatible with explosives, were handled in a room adjacent to Booster Room 2. The chemicals were used to manufacture flux. Explosive materials on the pouring tables and surrounding floor were swept up and added to a subsequent batch of base mix in a mixing pot. One forklift serviced both booster-production and flux-manufacturing areas.	The floor of the adjacent building in which the flux operations were conducted was about six inches below the level of the floor in Booster Room 2. Any contamination from floor sweepings would need to be elevated to the booster room. The raw materials for the flux operations were stored separately from the raw materials for the booster fabrication. Workers trained in booster fabrication and flux-composition manufacture did not enter each other's work areas. The operations of melting and pouring the explosive compositions would have the effect of self-cleaning the pots, which would minimize the effects of cross-contamination even if present. Periodic steam cleaning of the booster rooms would remove chemical contamination.
Mechanical Failure of Bearings	Improbable	Enough energy could be generated by a bearing failure to generate heat and sparks, thus igniting nearby combustible material.	The transmission and bearings were located inside a casing outside the pot in which the explosives were being mixed. The transmission was new, and the bearings reportedly were being greased periodically. A bearing failure would be unlikely at or shortly after startup and would not contact the explosives.
Propane Leak and Fire	Improbable	Ignition of leaking propane in the booster room could cause detonation of explosive raw materials. Propane was used to fire the steam boiler.	Leaking propane is easy to detect due to the addition of an odorizer. There were workers who walked close to the boiler room as they came to work, and there were workers working in the vicinity. Ignition of a buildup of propane in the boiler room would be unlikely to impact explosives in the booster room, which was separated by distance and two concrete-filled block walls. A propane fire by itself would give nearby workers a chance to respond. There was no indication of such a response.

Potential Ignition Source	Relative Likelihood	Supporting Factors	Factors that Reduce Likelihood
Steam Boiler Explosion	Improbable	The steam boiler had not received a final inspection.	The boiler was a low-pressure boiler with pressure relief at 15psi. Inspection of the boiler following the explosion showed no signs of an internal explosion.
Sabotage	Improbable	A variety of means could be used intentionally to detonate explosives.	The Sheriff and BATF investigation found no evidence of a criminal nature or of an intentional act.

APPENDIX B: Seismology Report

Seismic Analysis of the Kean Canyon Explosion

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Abstract

An unfortunate industrial accident at a the Sierra Chemical Company plant east of Reno, Nevada, consisted of two explosions that occurred within about 3.5 *seconds* and were separated by ≈ 75 meters along a direction of S33°E (US Chemical Safety and Hazard Investigation Board). Using an high precision cross-correlation method applied to both seismic and air-waves recorded at several seismic stations in northern Nevada, we are able to resolve the relative locations, azimuth between the sources and the chronology of two explosions. The difference in moveout of air-waves between the two explosions, measured at several stations, associates the southern site with the second explosion. The separation of explosions, based on an analysis of these air-wave arrivals, at 3 stations is about 73 meters with an uncertainties ranging from ±7 to 21 meters. We obtained only a single estimate of source separation using P-waves which is 80 meters with a larger uncertainty of ±78 meters. We did a simultaneous determination of the separation and the azimuth of the explosions which combines the moveout at different stations. The best solution occurs with a separation of 73.2 meters with the second explosion occurring at azimuth of S35E from the first. These estimates are well within uncertainties of investigation by the US Chemical Safety and Hazard Investigation Board. From the relative spectral amplitudes of P- and air-waves, we suggest that explosion B had downward directivity, while A may have been more upwards directed. The corner frequency of the P-waves is much smaller than expected for the physical dimension of the explosions, indicating that attenuation is exerting a major influence on the P-wave spectrum at high frequency. The results from this analysis suggests that relative

location of small earthquakes with nearly identical seismograms can be achieved with similar accuracy using a regional seismic network.

Introduction

Two explosions occurred ≈ 3.5 *seconds* apart at the Sierra Chemical Company facility ≈ 20 km east of Reno, Nevada, on January 7, 1998. The events were heard and felt throughout the Reno-Sparks metropolitan area. Unfortunately, four people lost their lives and six more individuals were injured in the explosions. The recently organized United States Chemical Safety and Hazard Investigation Board (CSB), with the cooperation of several state agencies, initiated an investigation into the accident with the long range goal of improving the safety at explosive manufacturing facilities. An important aspect of the investigation was determining the chronology of events.

View of booooster room 1 following the explosion, with west wall still standing. The five workers in this room survived.

For More on CSB investigation see http://www.chemsafety.gov

The two explosions were recorded on several stations of the western Great Basin seismic network (Figure 1). From these records, the estimated origin time of the first explosion was 15:54:03.300. ±30*sec* GMT (7:54 AM PDT), with approximate location 39°North 31.8 minutes, 119°West 38.0 minutes. However, based on information provided by the CSB *(John Piatt, personal communication)* the location is 39°North 32.5 minutes, 119° West 38.1 minutes. We used the CSB's location in our subsequent analysis based on seismograms; it is well within normal uncertainties for earthquake locations. Treated as an earthquake, the magnitude of the event is estimated to be M ≈ 2.0. Four of the stations that recorded the explosion were recently installed digital broadband seismographs that were acquired through a grant to the University Nevada Reno from the Keck Foundation. Several of the seismograms are shown in Figure 2. The seismograms include two conspicuous P-wave arrivals, followed by an "N-wave" *(Kanamori et al., 1991)* that is created by the shock wave traveling in air. An examination of the seismograms (Figure 2) shows that there are two explosions separated in time by about 3.5 seconds. The phase that appears to be an S-wave in Figure 2 is the P-wave arrival from the second explosion, although there may be some amplitude contribution from an Lg phase. The station geometry relative to the source area is such that the P-wave arrival from the second source is nearly coincident with the expected Lg arrival from the initial event at both PAH and WCN. Evidence for the interpretation of these phase arrivals is based on the nearly same time separation observed in the air-wave arrivals at several stations. The larger amplitude of the P-wave and air-wave phases for the second event suggests that this was the larger of the two explosions, although the coupling of the explosion must also be taken into account in this interpretation.

Figure 1. Westert Nevada digital seismic stations, location of the chemical explosions and the Reno Sparks, and Carson City urban areas.

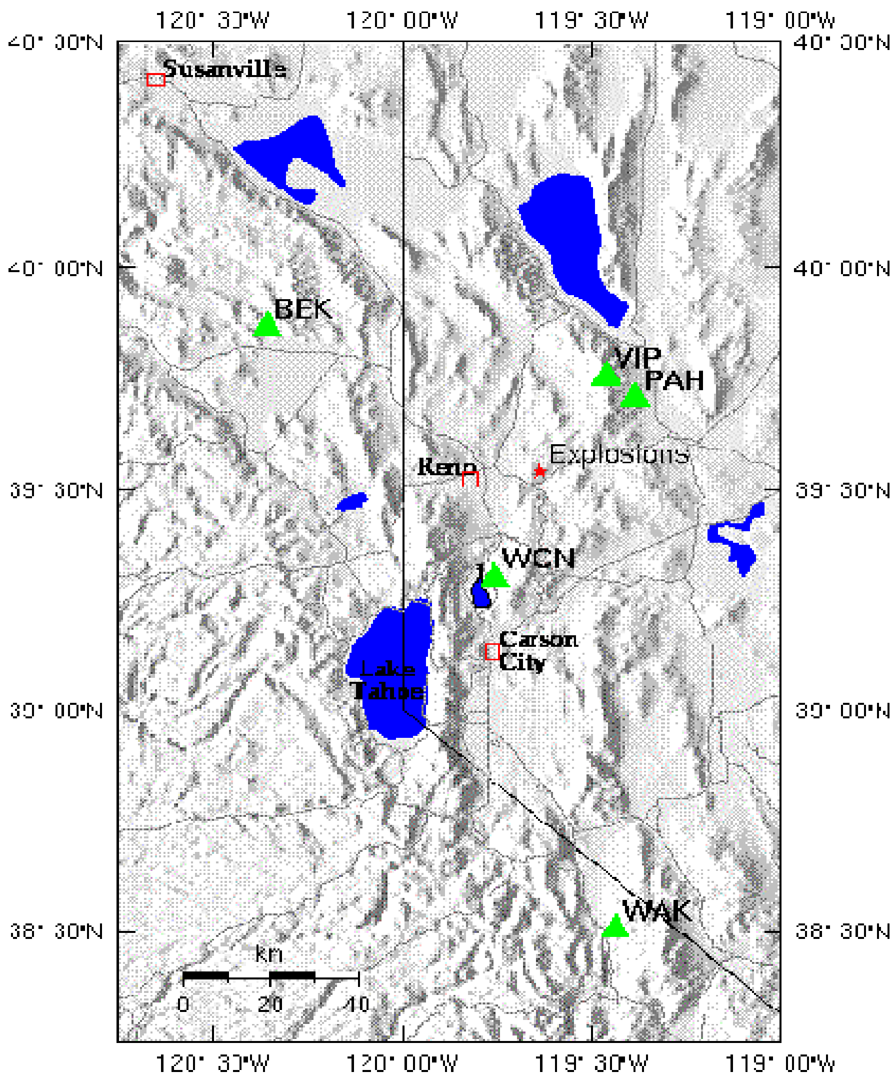


Table 1. Station locations, and their distances and azimuths to the estimated explosion site.

Code	Name	Latitude°N minutes	Longitude°W minutes	Elevation (km)	Distance (km)	Azimuth (°)
WCN	Washoe City, NV	39 18.10N	119 45.38W	1.50	28.6	201.5
VIP	Virginia Pk., NV	39 45.24N	119 27.65W	2.49	27.9	32.2
PAH	Pah Rah Range,NV	39 42.39N	119 23.05W	1.50	28.3	49.4
BEK	Bekwourth, CA	39 52.00N	120 21.52W	1.74	71.8	300.4
WAK	Walker, CA	38 30.26N	119 26.23W	1.89	116.3	171.5

Figure 2a.

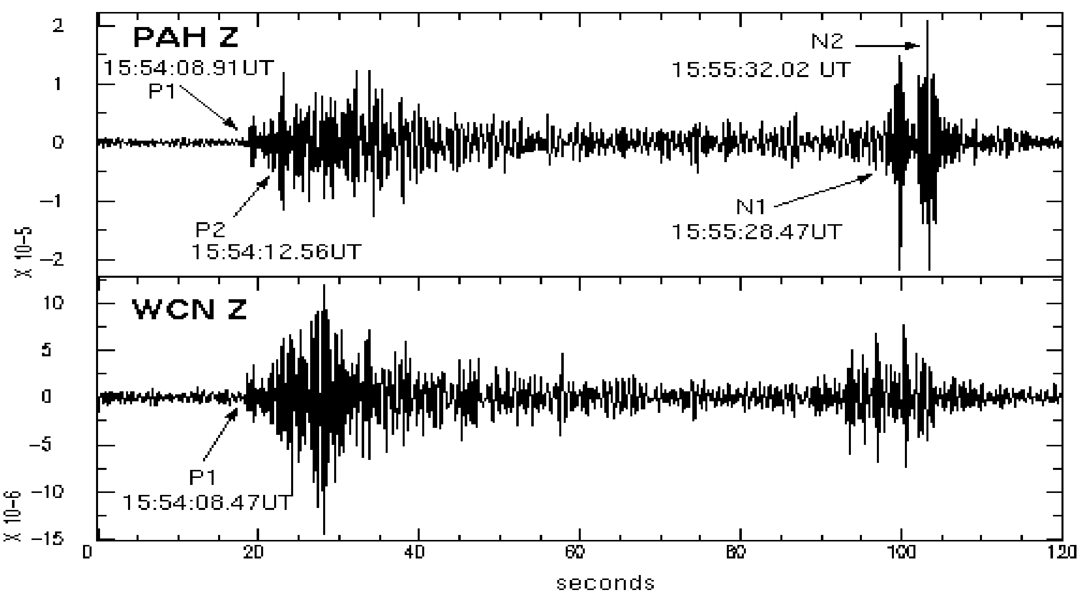
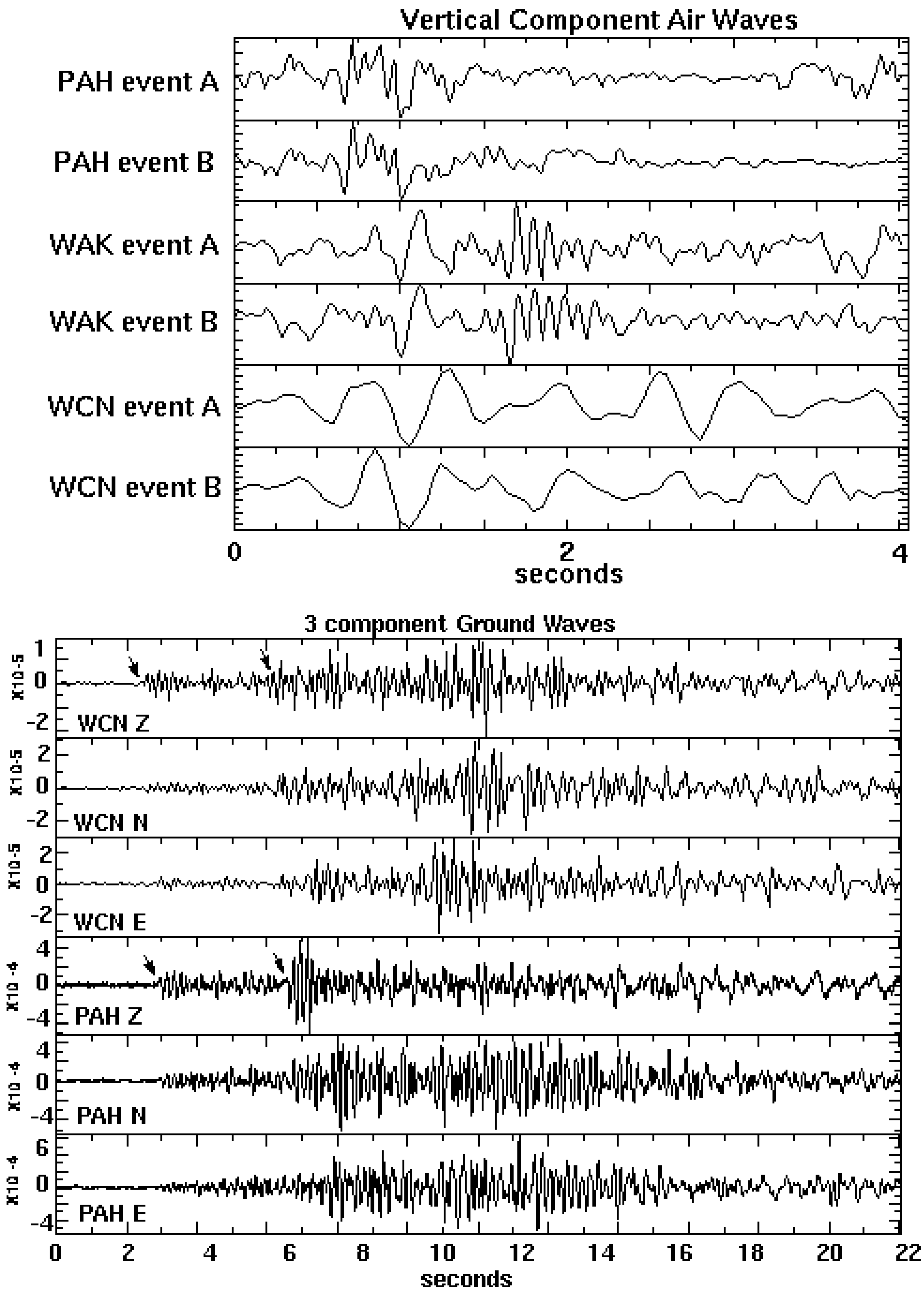


Figure 2a. Vertical component seismograms from station PAH and WCN. The P1 and P2 labels indicate P-wave arrivals for explosion A and B. N1 and N2 labels indicate the N-wave (air wave) arrivals for explosion A and B.

Figure 2b. Seismograms of low-passed filtered vertical component air waves and 3 component seismic waves used in this analysis. The arrows point to the arrival of P-wave of explosion A and B.

Figure 2b.



In their request to the Seismological Laboratory *(John Piatt, personal communication)*, the CSB reported that two explosions were separated by a horizontal distance of approximately 250 feet (76.2 meters), along a strike of 147° . Uncertainties in these measurements are due to uncertainty on where the "centers" of the explosions were located. The northern explosion occurred in a building that was formerly about 40 feet by 40 feet in dimension *(CSB, 1998)*, and the southern explosion left a kidney-shaped crater that was about 30 feet across and 50 feet long (John Piatt, personal communication). A circular approximation would have a radius of 40 feet. Based on these dimensions, the separations between the centers of the explosions could be uncertain by as much as several meters, and the azimuth could be uncertain by a few degrees. According to testimony to the CSB (John Piatt, personal communication), there were about 7500 to 8000 pounds of explosives (TNT or COMP-B) at the northern site, and about 15000 pounds of explosives (PETN) at the southern site. Based on several independent lines of evidence, the CSB has come to the conclusion that the northern explosion occurred first.

We are interested in these events because they provide the opportunity to test a cross-correlation method to estimate relative source locations. We have observed numerous cases of nearly identical seismograms called multiplets in routine monitoring activities, and have experimented with the cross-correlation of digital seismograms to estimate the spatial separation of seismic sources. By being able to actually measure the source locations on the ground, the resolving power and the errors associated with this methodology can be directly evaluated.

Analysis and Results

We located the initial explosion (explosion A) from the P-wave arrivals recorded at the UNR Keck digital stations and one helicorder record from an analog station (Table 1). The existing regional network of analog stations did not trigger on the explosion. We used the 1-D velocity model (Table 2) to estimate of the absolute location of the first explosion. Since the location determined from the P-wave arrivals of the first event is only 1.2 km from the known mapped location of the explosions, our confidence in the velocity model in Table 2 is increased.

Table 2. Velocity model used in location of explosion.

P-wave Velocity (km/s)	Depth to top of Layer (km)
3.0	0.0
4.5	1.0
5.5	2.0
6.0	4.0
6.1	7.0
6.2	12.0
6.4	18.0
6.8	28.0
7.8	38.0

To find the relative locations of explosions A and B, one requires knowing the precise time difference between the explosions, $t_b - t_a$, that can be measured from the records of P- and air-waves. We performed cross-correlations on windows of the P- and air-wave arrivals in the frequency domain *(Fremont and Malone, 1987)*. The frequency domain technique can establish finer relative time estimates that are below the limit imposed by the sampling interval. This is required for relative locations with a precision on the order of several meters. The time difference between the two explosions is proportional to the slope of the phase of the cross spectrum,

$$t_b - t_a = \frac{\phi(\delta f)}{2\pi \delta f} \qquad (1)$$

where $\phi(\delta f)$ is the phase of the cross spectrum over a frequency range delta f. The intercept is fixed at 0 Hz and a line is fit to $\phi(\delta f)$ by simple least squares. The seismogram with both explosions are windowed by 2 seconds around each of the P-wave and air-wave arrivals and then cosine tapered. The windowed seismogram of explosion A is then initially aligned by routine picking relative to the seismogram of explosion B, and the time shift from the slope of the phase of the cross spectrum is finally used to correct this initial alignment.

A measure of the coherency of the phase arrivals is used to determine the frequency range over which the slope of the cross-spectrum phase is analyzed. The normalized coherency between two time series measures the similarity of their shapes, ranging between 0, when they are completely dissimilar, to 1 when they are identical. The coherency in the frequency domain, C(f), between the Fourier transform of seismograms $s_1(f)$ and $s_2(f)$ is defined here following Menke et al. (1990),

$$C(t_b - t_a, \Delta f, f) = \frac{|< s_1^*(f) s_2(f) >|^2}{< s_1^*(f) s_1(f) > < s_2^*(f) s_2(f) >} \qquad (2)$$

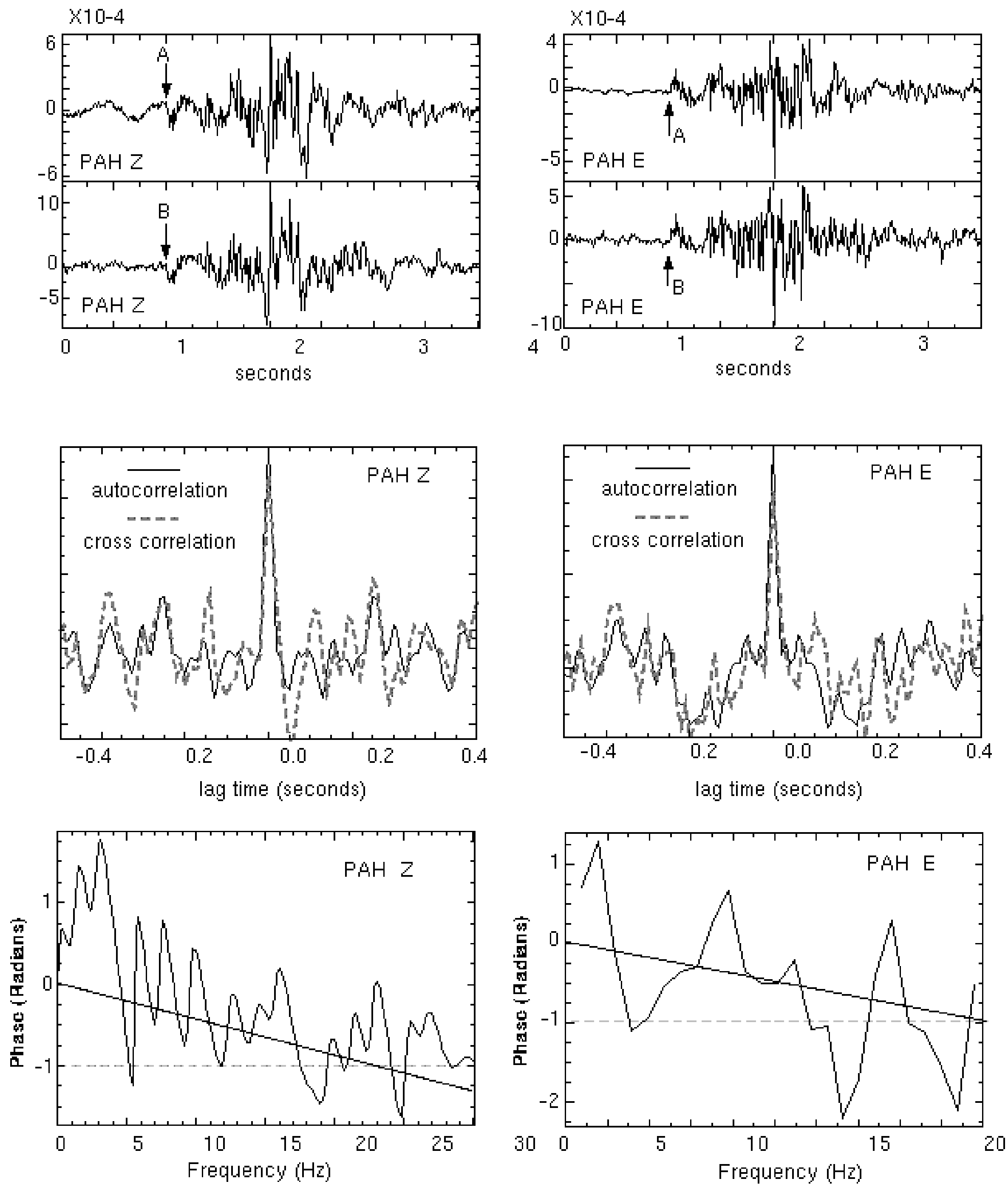
where f is frequency, < > denotes boxcar averaging over frequency interval Δf centered on f, and s* denotes complex conjugation. The windowed seismograms are shifted by $t_b - t_a$ as estimated from equation (1). We find that the coherency between phase arrivals falls-off at high frequencies, and therefore we only fit $\phi(\delta f)$ for f above 80% coherency. This fall-off is probably due to the slight difference in the travel paths from the source separation, later arrivals from the first explosion superimposed upon the record of the second, and possible differences in the details of the two source time functions. An example of the cross-correlation is shown in Figure 3, and the apparent time lags with uncertainties derived from these cross spectra are given in Table 3.

Table 3. Time after the first explosion until the maximum of the cross correlation of the first and second explosion.

Station	Compone nt	P-wave $t_b - t_a$ (sec)	Uncertainty (ms) *	Air-Wave $t_b - t_a$ (sec)	Uncertainty (ms) *
WCN	Z	3.599	11	-	-
WCN	E	-	-	3.403	10
PAH	Z	3.582	6	3.582	9
PAH	N	-	-	3.542	-
WAK	Z	-	-	3.330	11
WAK	N	-	-	3.330	-

*** Standard Deviation of phase spectra converted to apparent time separation between explosions.**

Figure 3.



The vertical and east-west component of air-waves recorded from PAH with the cross- and auto-correlation functions. The bottom panels show the slope of the phase of the cross spectrum are fit over the frequency range of > 80% coherency.

Based on the time separations from the cross-correlations method, we estimate L, the distance separation of the second event relative to the first as a function of θ, the hypothetical direction from the first source to the second, using:

$$L_{ij}(\theta) = \frac{c\,\Delta t_{ij}}{\cos(\theta - \theta_i) - \cos(\theta - \theta_j)} \qquad (3)$$

where c is either the air velocity of 343 m/s or P-wave velocity of 3000 m/s, Δt_{ij} is the difference in the times between the explosions at stations i and j, and θ is the azimuth from the first explosion to the i th station. The better resolution results from an analysis of the air-wave arrivals because of the substantially slower air velocity. L_{ij} is computed from values of ranging from 0 to 180° for the 3 station pairs to find a simultaneous best solution at $\theta \approx 145.1°$ (S35°E) and L $\approx$ 73.2 meters (Figure 4). The relative location estimates based on the P- and air-waves are shown in Figure 5 along with the error estimates. The results for the air-wave unambiguously indicate that the second explosion B was southeast of the first explosion A. This result leads to the conclusion that the initial explosion was at the northern site, which is consistent with the analysis of the CSB.

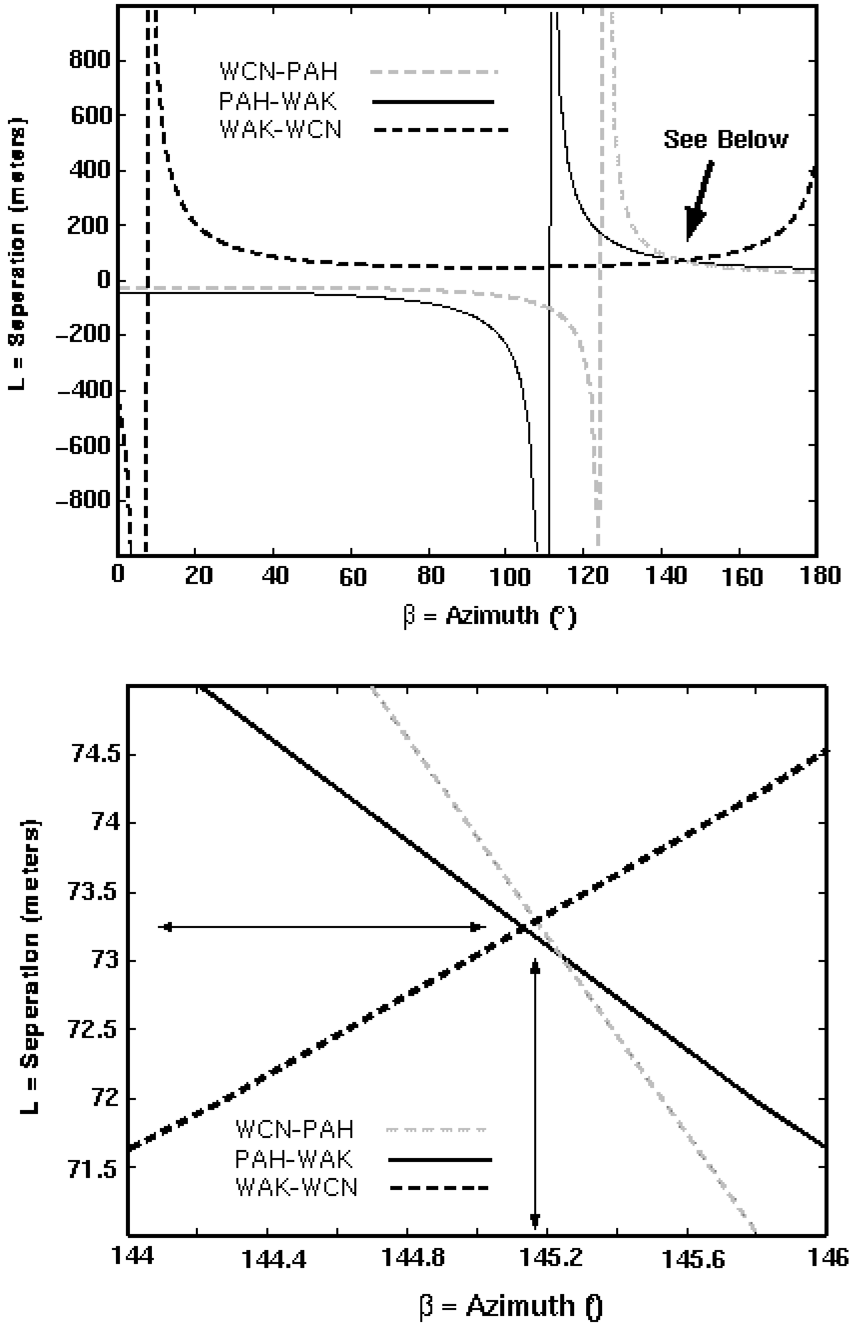


Figure 4. A plot of L, the source seperation versus β, the azimuth between sources. The arrows point to the best solution for L and β.

The relative locations based on the moveouts of these phases are, within error bars, consistent with the location of the second event based on the CSB investigation. The differences in separation between our estimate (73.2 meters) and the CSB estimate (76.2 meters) is small compared to the source dimensions, and the difference in azimuth between our estimate of S35°

E (145.1°) and the CSB estimate of S33°E (147°) is also within the range of angles that is allowed by the source sizes. The uncertainties in measuring $t_b - t_a$, shown in Table 3, corresponds to the standard deviation of $\phi(\delta f)$. This standard deviation is considered as the maximum uncertainty of determining the slope using equation (1). There is always a $2\pi n$ uncertainty in unwrapping the phase spectra but since an initial shift was performed, we expect *n* to equal around 1 and the maximum uncertainty in *n* to be less than 2π. The uncertainties in determining the slope of the cross phase spectra are then propagated through equation (3) by fixing β and using the correct polarities of the $t_b - t_a$ uncertainties. This gives the maximum uncertainty in source separation given only a pair of stations and their geometry. The importance in receiver geometry on uncertainty is shown by the difference in separation uncertainties, with ± 7 meters between PAH and WAK, which are almost along strike of the explosions, and ±21 meters between WCN and WAK, which are relatively more perpendicular to the strike. The $t_b - t_a$ uncertainties are not propagated through the simultaneous determination in L as a function of β because it is used to show the best combined estimates of these parameters.

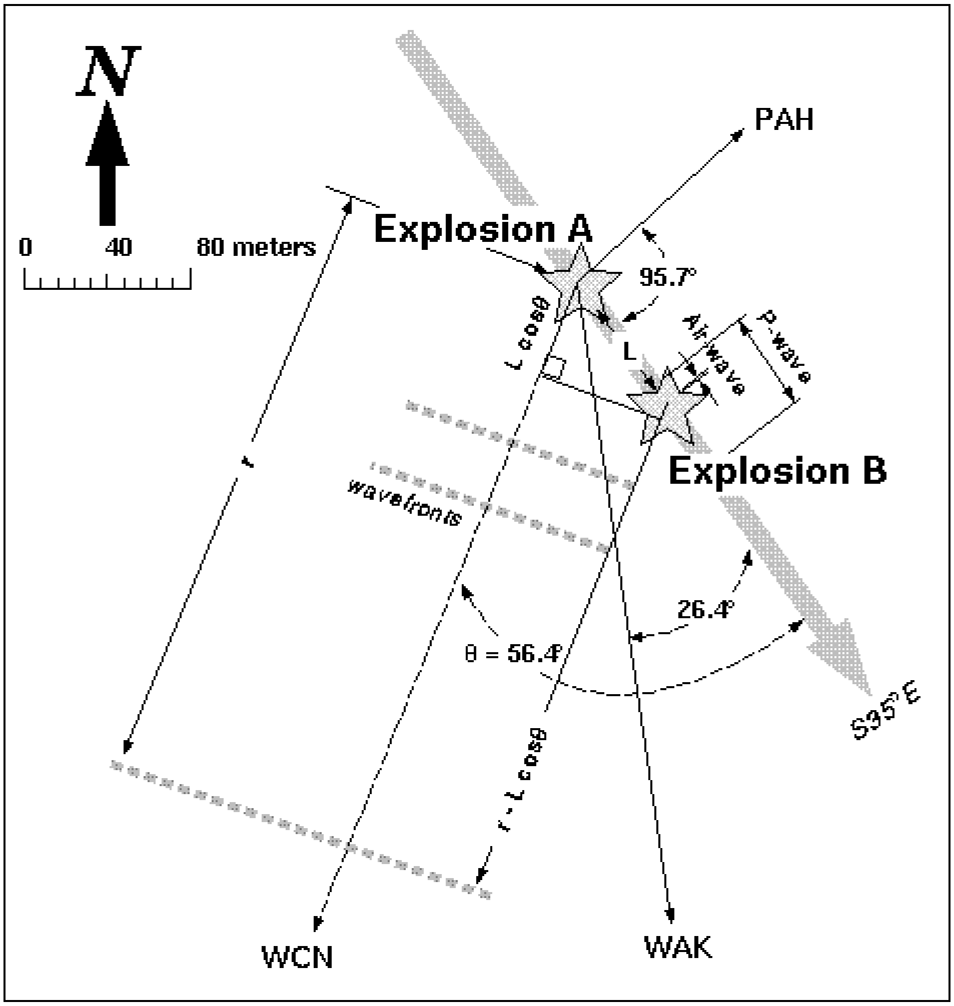


Figure 5. A Schematic map of the explosion site with likely geometry of explosions marked as "stars" and the estimated relative seperations shown as uncertainties along azmuith of S35°E. See equation (3) in text for variable definitions. The

There is no significant source of error associated with timing in the recorder itself. The digital stations maintain absolute timing by synchronizing with a GPS time signal that is broadcast from the Seismological Laboratory. The GPS signal is broadcast every second and a high precision oscillator in the seismograph unit is phase-locked to UTC by this pulse. A radio frequency delay of 44 ms, which occurs in the electronics and telemetry systems, is accounted for in establishing absolute time of the recorded waveforms. A timing mismatch of 1 msec between the GPS time and the internal clock time results in a clock correction that is reported by the instrument. Timing errors during regular operation rarely exceed several msec. Because the two explosions occurred within 3.5 sec, the absolute timing of the instrumentation is not critical, and only the error in the digitization rate is relevant. The manufacturer reports that errors in the digitization rate for the internal oscillator do not exceed 1 msec for any one sample and are expected to be on the order of 50 microsec. If the oscillator would drift more than 1 msec over any recording period, then a timing correction would be initiated by the instrument and its results would be recorded in the instrument log. For the air-wave, 1 *msec* would introduce an error of about 0.3 meters in the source location.

Atmospheric conditions that affect the speed of sound can shift the estimated separations slightly. We used an air velocity of 343 m/s *(Kinsler et al., 1982)*. For a 10% uncertainty in the assumed air velocity of 343 m/s, which is greater than expected, the relative source separation error would be ±7.0 meters, which does not impact our conclusion as to the relative source locations or chronology. A consistent wind velocity across the array on the morning of the blasts would not be significant; a 10 MPH wind is only 1.3% of the speed of the air-wave.

One of our objectives was to see if it is feasible to measure the separation between the events using the P- and S- waves. From Table 4, we see that the best estimate of the separation using the P-waves is 79.9 m, which is consistent with the estimates using the air-waves. However, the uncertainty in the time separation for the P-waves from WCN and PAH leads to a large uncertainty on the separation. The P-wave at WAK, 116 km epicentral distance, was too weak to provide a reliable separation. We consider these results to be very encouraging. With an adequate signal-to-noise ratio, the locations of closely spaced multiple events recorded at three or more stations should be resolvable.

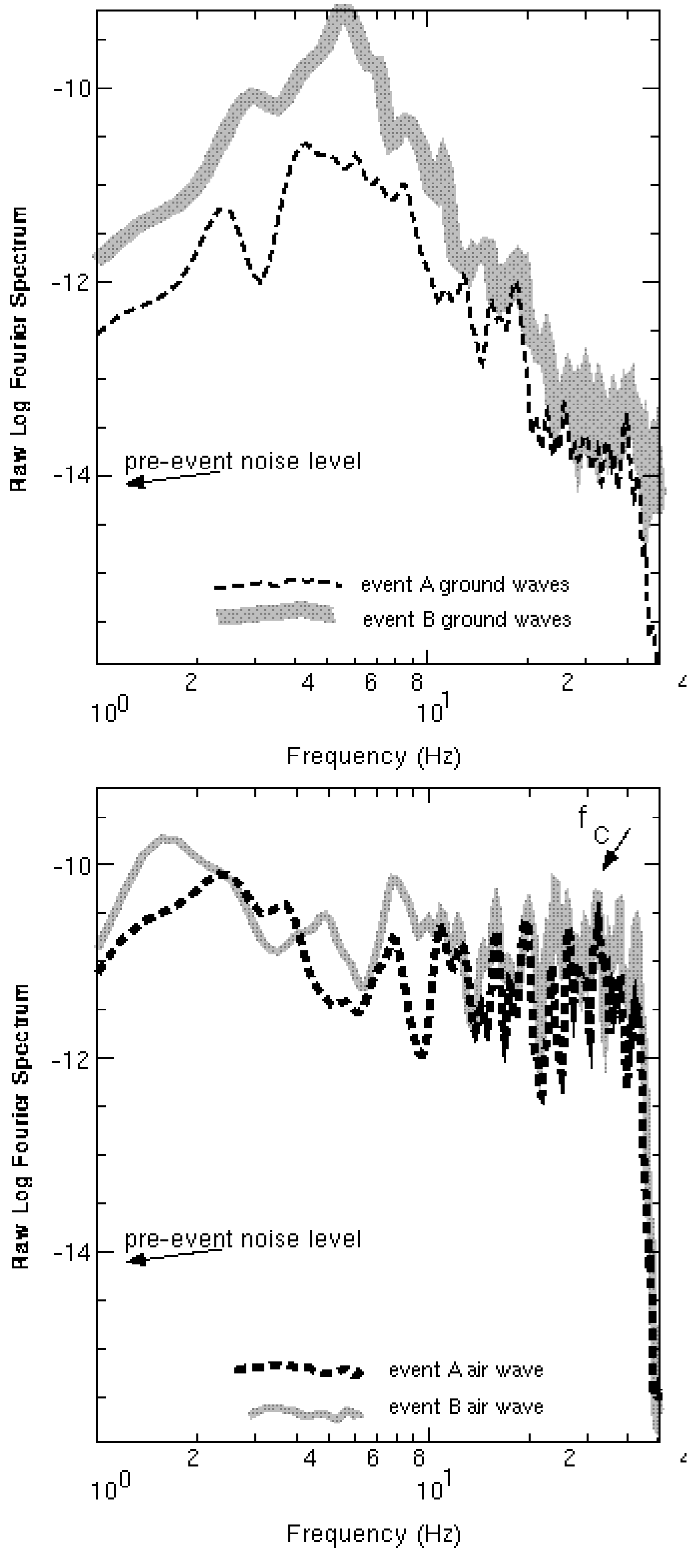
Table 4. Geometry and results of source separation estimation.

Path	P-wave (sec) *	Air-wave (sec) *	θ_j°	θ_j°	Separation (m)	Uncertainty (m)
WAK-PAH	-	0.2126	-26.4	95.7	72.3	66.36-80.14
WAK-WCN	-	0.0752	-26.4	-56.4	73.3	52.12-94.20
WCN-PAH	-	0.1374	-56.4	95.7	73.2	63.30-83.20
WCN-PAH	0.0144	-	-56.4	95.7	79.9	1.8-158.0

*** Δt_{ij} is the difference in $t_b - t_a$. between station pairs along path.**

Figure 6 shows the uncorrected spectra of the P-wave and the air-wave from the two explosions at PAH (Guralp CMG-40 velocity sensor). The three components are log averaged and then smoothed. Based on the P-wave at PAH, explosion B was 3 to 4 times larger than explosion A, consistent with reports that the second site "B" contained more explosives. The spectrum of air-waves of explosion B is only a little larger than explosion A. This may suggest that explosion B was more coupled to the ground, allowing more energy to be partitioned into the ground than into the air. The CSB hypothesized that the second explosion was triggered when debris from the first explosion crashed through the ceiling or skylight at the second site. If so, we speculate that the second explosion may have been triggered at the top of the stockpile, resulting in downward directivity and a different partitioning of energy between the ground and the air.

Figure 6. Uncorrected P-wave and air-wave



The spectral curves are the smoothed log average of the three components of motion. The arrow points to peak spectral value of a noise window before explosion A.

The physical dimensions of the explosions, like the dimensions of earthquakes, should be related to the corner frequency, fc, measured from the Fourier spectrum. To test this, we used an equation for the earthquake source radius r from Brune (1970),

$$r = \frac{2.34\,c}{2\pi f_c}, \qquad (4)$$

where c is either the P-wave velocity or the speed of sound in air. The measured crater of the second explosion B was about 12 meters across and 1.8 meters deep, suggesting that = 6 meters is the expected source radius. The northern explosion A did not leave a crater, consistent with upwards rather than downwards directivity. The building was formerly 40 feet by 40 feet (CSB), giving an upper limit to the source radius of about 6 meters.

The Fourier spectra from the air-waves, in Figure 6b, are relatively flat from 1 Hz to above 30 Hz. The high frequencies of the air-waves are limited by the anti-aliasing filters in the recorder ($\approx$ 40 Hz). The spectrum from explosion A might suggest the presence of a corner at about 30 Hz, which from equation (4) would give a source radius of 4 meters. Such a result is reasonable considering the independent information about the size of the building.

The P-wave spectra fall off rapidly above 6 Hz, so we take 6 Hz to represent the corner frequency of these spectra. In equation (4) we do not have the P-wave velocity, so arbitrarily assume it to be 1000 m/sec, which we consider reasonable for weathered bedrock. With this combination of parameters, equation (4) gives $r \approx 60$ m, which is about a factor ten larger than the estimate from the air-wave and from ground observations. We therefore suggest that attenuation along the path has played a major role in decreasing the amplitude of high frequency P-waves. The P-waves spectra have decreased to amplitudes comparable to the pre-event noise above 20 Hz, implying that the attenuation eliminates the chance to use P-waves to estimate the source dimension for such small events whether earthquakes or explosions. For earthquakes, the P-waves would only need to pass through the near surface zone of severe attenuation once, so resolution of a high corner frequency should be somewhat better than in this case.

Conclusions

We have analyzed the relative arrivals of both seismic P- and air-waves at a number of seismic stations to estimate the spatial separation and orientation of two closely-spaced explosion sources that occurred within approximately 3.5 seconds. By using precise timing from the cross-correlations of the air-waves from multiple stations, and assuming an air velocity of 343 m/s, we estimate that the separation is about 73.2 meters. This accuracy results from the relatively slow velocity of the air phases. We also estimate that the two sources align along an azimuth of S35° E. The separation and orientation of the two explosions were well within uncertainties of the data provided by the CSB. The separation determined from the relative P-wave arrivals is similar, 80 meters. From the relative spectral amplitudes of P- and air-waves, we speculate that explosion B may have had a downward directivity, whereas explosion A may have been more upwardly directed. From the viewpoint of forensic seismology, this experiment was successful, in that the air-waves unambiguously demonstrate that the northern of the two explosions occurred first. We confirm that the relative separation of sources can be determined precisely using only a pair of regional seismic stations. We are encouraged that this approach can also be applied to earthquakes.

Acknowledgments

We acknowledge the Sierra Chemical Company, and everyone else who was so adversely affected by this unfortunate event. David vonSeggern and Diane dePolo estimated the magnitude of the event. We thank the Keck Foundation for their generous gift that allowed installation of the digital stations used in this research. This work was also made possible through financial support provided by U.S. Geological Survey NEHRP grant 1434-94-G-2479.

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APPENDIX C: Bureau of Alcohol, Tobacco and Firearms Report

DEPARTMENT OF THE TREASURY
BUREAU OF ALCOHOL, TOBACCO AND FIREARMS

OFFICE OF LAW ENFORCEMENT

Statement of Explosives Technology Branch

To: RAC Robert Stewart
Bureau of Alcohol, Tobacco and Firearms
350 South Center Street, Room 380
Reno, NV 89501

I/N: 745904-98-0009

ETB: W-98-027

Date: January 20, 1998

On January 8, 1998, the Midwest Region Response Team was directed to respond to the Sierra Chemical Plant near Mustang, Nevada. An explosion in their booster plant on January 7, 1998 resulted in the death of four employees and the destruction of the plant.

The booster plant was comprised of two large offset buildings, a break room, a laboratory, and a PETN drying room. The areas of concern are the two large offset buildings, containing booster rooms one and two, and the PETN drying room. Both of these areas were of industrial type construction consisting of a concrete foundation, cinder block walls, and a plywood roof with a composite of fiber insulation and an external rubberized material. These areas were bordered by a rear dirt berm and an approximate 30 degree downslope towards the front, on the south side.

The two large offset buildings comprised, from left to right, booster room one, a storage area, locker room, booster room two, flux room, and tool room. This combination of buildings sat at the top of a hill at the base of a mountain.

Located approximately 50 yards downhill from booster room one was the PETN drying room. This building was comprised of three areas. The first room was empty and allowed workers to shield themselves from the weather while they downloaded PETN. The second room contained a centrifuge and an area where the PETN would be hanged to drip dry. The third and final room contained racks where the PETN was laid down to complete the drying process. This structure was located north, on an uphill grade approximately 100 yards from the entrance of the plant.

Primary areas of interest were booster room two, and the PETN drying room. Booster room two included six mixing kettles aligned in a U shape toward the rear wall, two circular pouring tables centered in front of the kettles, and a cooling bin toward the left front wall. The mixing kettles were numbered one through six from right to left. Mixers 1, 2, 5, and 6 were large kettles, and could contain approximately 100 pounds of Composition B explosives. Mixers 3 and 4 were small kettles, and could contain approximately 80 pounds of Pentalite explosives. Mixers 1 and 6 were never used. Booster room two used steam to mix the explosives verses heated water used in room one, and all mixers were hydraulically controlled. In addition, booster room two was new and had only been operational for a couple of months.

Statement of Explosives Technology Branch

I/N: 745904-98-0009

Reportedly, a crystaline coating adhered to the ceiling of booster room one. Interviews revealed the origin of the crystals. The crystals resulted from emitting vapors in the mixing process. These supposed explosive vapors would rise to the ceiling and resolidify in the form of crystals.

A question was also raised as to whether or not the mixing kettle motors in booster room two were in fact explosion proof. These types of motors prevent the introduction of inadvertent sparks from electrical current into the mixing kettles. At the time of this report, this could not be verified.

On the morning of the accident, approximately 3,000 pounds of explosives were contained in booster room two. Conversely, the PETN drying room, as outlined above, contained approximately 11,000 pounds of wet PETN that morning. And according to an employee, the centrifuge was turned off and no one had yet gained entrance to the drying room prior to the explosion.

On this day, two people were assigned to work in booster room two. One was late for work and the other was seen in booster room one at approximately 7:30 a.m. At that time, booster room one, according to interviews, had been operational for a couple of hours and contained more explosives than booster room two, but no specifics could be given. All that could be ascertained was that each booster room could contain approximately 5000 pounds of explosives.

After being seen in booster room one, the employee scheduled to work in booster room two had to proceed to the employee locker room. According to interviews, it was customary for an employee to take up to 10 minutes to change clothes in the locker room prior to beginning their shift. This puts the employee entering booster room two at approximately 7:40 a.m. (the blast occurred at 7:54 a.m., leaving about 14 minutes of operational time for the employee). Using 7:40 a.m. as the time of entry, the employee would enter booster room two, ensure that the appropriate amount of explosives were present to start the mixing process , inspect the mixing kettles (through interviews, it was determined that the kettles were not always cleaned but procedure is to leave the pots empty), and start the mixing process in the large, Composition B pot, which could take up to an hour. Since one employee was late, the only kettle that should have been started the morning of the accident was kettle number 5. Procedure states that this kettle would be started, and at the latest possible moment, the smaller, Pentalite kettle would be started. The pouring process would then begin with an 80/20 Composition B and Pentalite mixture, respectively.

Post blast investigation revealed that structural and kettle fragmentation had been thrown to the northeast and northwest side of the mountain, which buttressed the structure containing both booster rooms. Lighter fragmentation had been propelled eastward into an adjoining canyon. Small pieces of what should be mixing kettle 5, to include the drive shaft, were found on the hill to the east and more, small kettle pieces were found to the west. These pieces of fragmentation displayed detonation effects. The fact that these pieces were found at far distances established not only a blast pattern, but also the presence of immense force. These factors indicate that high explosives were present in what procedure states should be mixing kettle 5.

Further investigation of the PETN drying room blast crater indicated the absence of fragmentation from booster room two in or around the area. Additionally, a blast pattern was outlined on the grass on the east hill with dust that can be followed directly back to the PETN drying room crater. This blast pattern is indicated by the grass on the hill being blown down in a northeast direction. In addition, fragmentation from the trailers that were staged next to the tool room, hence booster room two, was found on the east hill covered with dust from the PETN drying room crater. Also, the right wall of booster room one was sandwiched between the concrete floor and its front wall. Finally, a seismographic report states that the second detonation was of greater magnitude than the first.

All of these indicators state that booster room two detonated first, followed by the PETN drying room. If the PETN drying room had exploded first, fragmentation from booster room two would have been present in and around the PETN crater. Scene processing indicates that this is not the case. The detonation of booster room two created fragmentation that dispersed and hit the PETN drying room, causing the PETN drying room to detonate. This secondary detonation created a detonation wave and fragmentation that formed a blast pattern originating from the PETN drying room.

The grass on the east hill was blown down in a northeast direction, displaying a blast pattern, and again indicating that the PETN drying room detonated second. If the PETN drying room had detonated first, the grass would have blown the grass in a northeasterly direction, and then the blast from booster room two would have blown the grass in a easterly direction. This is not the case.

Trailer fragmentation on the east hill is covered with dust from the PETN crater, which outlines the blast pattern mentioned above. This indicates that booster room two detonated and threw trailer fragmentation to the east. Then the PETN drying room detonated and covered the trailer fragmentation with its dust. Had the opposite occurred, the trailer fragmentation would not have been covered by dust from the PETN crater, it would have been laying on top of it and the blast pattern would, again, lead back to booster room two.

When looking up the hill, the right wall of booster room one was blown down, followed by its front wall, which landed on top of it. This indicates that booster room two exploded, and its pressure wave knocked down the right wall of booster room one. Then the PETN drying room exploded and its pressure wave knocked down the front wall of booster room one.

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Finally, a seismographic report states that the second blast was greater than the first blast. This correlates to the fact that there were more explosives in the PETN drying room than in booster room two. Hence, booster room two detonated, followed by the PETN drying room.

In conclusion, it is the opinion of the undersigned that booster room two detonated and then the PETN drying room detonated. Exactly what caused the booster room to explode is unknown. However, there is no evidence of any criminal act and, thus, the explosion was accidental.

Lori L. Stark
Explosives Enforcement Officer

Jerry A. Taylor
Explosives Enforcement Officer

EXPLOSIVE	CHEMICAL NAME	PROPERTIES	INITIATION SENSITIVITY			
			IMPACT		FRICTION (NEWTON)[1]	ELECTROSTATIC (JOULES)[2,3]
			(Newton-meters)[1]	LASL[2] (cm)		
TNT	2,4,6-trinitrotoluene	Pale yellow crystals if granulated, or flakes. Density of crystals: 1.65 g-cm^{-3} MP = 80.2°C (176.4°F)	15	157	>353	0.46-2.75
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazocine	Colorless crystals Density: 1.82g-cm^{-3} MP = 204°C (399°F)	7.5	23.3	120	0.22-0.55
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine	Colorless crystals Density: 1.96g-cm^{-3} (β modification) MP = 275°C (527°F)	7.4	26.1	120	0.20-1.03
PETN	Pentaerythritol tetranitrate	Colorless crystals Density: 1.76g-cm^{-3} MP = 141.3°C (286.3°F)	3	12.5	60	0.19-0.36

NOTES:
1 (Kohler and Meyer 1993)
2 (Gibbs and Popolato 1980)
3 Results for a brass electrode.

APPENDIX E: Response To Alternative Scenario

Comments were submitted to CSB for its consideration of an alternative scenario to the one presented by CSB investigators at the Board of Inquiry in Reno, Nevada, on April 16, 1998. The alternative scenario contends that the PETN Building exploded first, followed by a blast seconds later in Booster Room 2, and that the initial blast was caused by possible sabotage to cover the theft of a large quantity of PETN or some other unknown reason.

This appendix contains the CSB investigators' response to this alternative scenario. It also contains a summary of the arguments opposing the CSB scenario, and the CSB investigators' response.

The comments did not provide any conclusive evidence or analysis causing the CSB investigation team to alter its conclusions regarding the sequence and cause of the explosion at the Kean Canyon plant. Subsequent examination of the evidence has actually strengthened the CSB's conclusions related to the sequence of the explosions, which refutes the claims made in the comments.

- The University of Nevada, Reno, provided an analysis of seismic data that their seismologists believe demonstrates conclusively, based on the relative locations of the blasts, that the first explosion occurred in Booster Room 2 and was followed by the explosion in the PETN Building.

- In addition, explosives modeling experts at the Department of Energy's Oak Ridge National Laboratory compared the quantities of explosives present in the two locations to the seismic data showing that the second blast was stronger than the first. They found the quantities of explosives correlated well with the first explosion occurring in Booster Room 2, followed by the explosion in the PETN Building.

- This information, coupled with the observation that the last movement of the flatbed truck located over the edge of the slope south of Booster Room 2 was uphill, away from the PETN crater, all prove that the sequence of explosions as described in this report is correct.

EVIDENCE RELATED TO THE SEQUENCE OF EXPLOSIONS

The comments regarding the sequence of explosions and the CSB investigators' response are summarized below.

1. **Comment:** The pattern in the grass on the hillside east of the plant cited by the BATF investigators on initial entry is not meaningful because of the distance from the grass to the buildings of about 200 feet.

CSB: The grass patterns observed by the BATF support the contention that the PETN Building explosion occurred second because the grass pointed away from that location.

2. **Comment:** A blast from the PETN explosion caused all the damage that resulted in the layering near the Hot Water Boiler Building. [This is the building CSB refers to as the “Boiler Building” and which is labeled “Main Electrical Panel and Boiler” in Figure 3.] The blast wave from the explosion in the PETN Building pressurized Booster Room 1, which blew out the seven- by ten-foot sliding door which provided access to the platform on the east side of Booster Room 1. The same blast wave destroyed the walls of the Hot Water Boiler Building and blew the west half of the roof north, where it came to rest leaning against the south wall of Booster Room 1 near the loading dock. The second half of the roof landed upside down on the sliding door.

CSB: Layering of material is considered by the investigation team to be a helpful indicator of sequence. The layering observations provide strong corroborating information that helped the investigators establish the sequence of events.

The first issue raised by the comment was whether there were three layers or two layers of material on top of the Booster Room 1 sliding panel door. There were three layers of material. The Boiler Building roof slab and concrete cap were clearly evident. Below the Boiler Building roof slab was another piece of concrete that was part of a wall of the Boiler Building. The chunk of concrete underneath the Boiler Building roof slab was sandwiched between the Boiler Building roof slab and the Booster Room 1 sliding panel door. This chunk of concrete from the Boiler Building wall was moved by the incident investigation team just prior to lifting the Booster Room 1 sliding panel door to inspect under it. The Boiler Building wall material was on the Booster Room 1 sliding panel door and was clearly not part of the Boiler Building roof slab. Rather, it was located between the two pieces. The ground under the Booster Room 1 sliding panel door was free of debris from the Boiler Building or the PETN Building. This fact establishes that the Booster Room 1 sliding panel door reached the ground before debris from either of these sources.

The second issued was whether the south wall of the Boiler Building moved through the Boiler Building. The comment quotes a statement made by a CSB investigator: “The south wall of the Boiler Building was essentially blown through the building and landed on top of that door, and then the roof came down on top of that, giving us three layers of material.” This response indicates the writer of the comment misconstrued this statement. From all of the comments, it is clear that the writer assumed the statement meant that the entire wall went through the building intact and landed on the sliding door. What was actually meant by the statement was that the south wall of the Boiler Building collapsed into the Boiler Building. The collapse of the south wall allowed the Boiler Building to be pressurized, causing the walls to move outward. Chunks of the Boiler Building’s concrete walls landed on top of the Booster Room 1 sliding door that was on the ground at the north-east corner of the Boiler Building. Only a small section of the Booster Room 1 sliding panel door had wall material on it.

The comment also questioned the movement of the Booster Room 1 sliding panel door. It concludes that it would be "very improbable that a blast effect from the PETN Building traveling south to north demolishing a massive concrete building in its path would not entrain the light-weight door panel." This conclusion is not justified by the physical conditions present during the blast. There would be very turbulent conditions due to the effects of the topography of the site and the Boiler Building. It is more reasonable to conclude that the Booster Room 1 sliding panel door would remain on the ground, for two reasons: 1) the door panel was laying flat on the ground after the Booster Room 2 blast, and therefore had a low profile to the PETN blast effects, and 2) the Boiler Building shielded the ground behind it from the blast effects and therefore the Booster Room 1 sliding panel door remained in its final location.

The scenario proposed by the comment is not probable for an additional reason. The concept of the PETN Building blast causing the Booster Room 1 sliding panel door to be propelled to its final location so that the Boiler Building could fall on top of it is not credible. There were delays between the time the blast effects reached the Boiler Building and the same effects reached Booster Room 1. There were additional time delays needed to create the differential pressure to propel the Booster Room 1 sliding panel door from the building. There were still more delays needed for the door to travel from Booster Room 1 to the boiler room and land on the ground. Meanwhile, the Boiler Building walls, the tank, and the roof had only to fall to the ground with the aid of the blast. The scenario presented by the comment is highly unlikely given the photographic evidence of the undisturbed incident scene. Based on the physical evidence, the investigation team maintains that the source of differential pressure that led to the panel door movement was the explosion in Booster Room 2 and that the Booster Room 2 explosion occurred before the PETN Building explosion.

3. **Comment:** The configuration and construction of Booster Room 2 resulted in a highly directional blast which would have left the PETN crater free of debris if the second explosion had occurred in Booster Room 2. Further, the one piece of roof debris in the crater was cited as evidence that the first explosion occurred in the PETN Building.

   CSB: (See response to comment 7.)

4. **Comment:** The PETN explosion propelled the empty pneumatic tank originally located at the corner of the change room to an intermediate position leaning against Booster Room 2. The second explosion in Booster Room 2 then blew the tank and components to their final locations. This is proposed as the explanation for the upper lid being found southwest and pneumatic piping that fed into the lid to the southeast. Splattering noted on the top of the pneumatic tank was the result of the Booster Room 2 explosion melting and dispersing roofing material onto the lid of the tank.

   CSB: The sequence of events and explanation of the damage in this comment is not consistent with the actual damage sustained by the tank. The most significant contradiction in the comment's description is that the conical section at the base of the tank was pushed into the cylindrical portion of the tank, turning that part of the tank inside out. If the tank was leaning up against the building as described by the comment after the PETN explosion, the base of the tank would be pointing away from Booster Room 2 at the time of the Booster Room 2 explosion. This position would have resulted in greater damage to the sides and top of the tank and does not account for the base of the tank being turned inside out.

The sudden pressurization of the tank when the conical section was forced up through the base of the tank and violent acceleration due to the blast in Booster Room 2 explains the damage and eventual position of the various components of the tank.

The comment noted black spattering on the top of the tank lid, which they believe came from the asphalt roof material. There are many ways this material could have been deposited on the top of the tank. One of these is from the plume of the fire from the warehouse. Trucks in the lower Frehner Construction Company truck lot approximately 1200 feet from Booster Room 2 showed similar black spattering on the hoods.

Based on the physical evidence, the investigation team still concludes that the tank was damaged and propelled by the explosion in Booster Room 2. And that the location of the tank confirms the sequence of events to be first an explosion in Booster Room 2 followed by the PETN Building explosion.

5. **Comment:** The flatbed truck, which was facing east, and located just south of the change room, was struck by the blast from the PETN building which lifted the front of the truck and rotated it counter-clockwise 45-60 degrees to the north. The second blast from Booster Room 2 then propelled the truck south, where it came to rest on the edge of the terrace slope.

   CSB: The comment has several major deficiencies. First, it does not address the riprap evidence (discussed in Section 3.4 of the report) showing that the last movement of the truck was uphill, away from the PETN Building and toward Booster Room 2. Second, the comment does not address the cargo rack being on the Booster Room 2 side of the truck on top of building debris, including part of the stand from one of the two small mixing pots. The other observations and conclusions in the comment are inconclusive because they are sequence independent (damage to cab and grill), can have multiple explanations (small piece of wood stuck in the grill), or are unsupported conclusions (breaking of the base plate weld).

   Photographic evidence shows a piece of the sheet metal wall from the production buildings jammed up under the frame over the back side of the rear dual tires on the passenger side of the truck. The portion of this sheet metal that extended beyond the outside dual tire was wrapped up and back around the outer member of the flatbed frame. The siding was blown out by the Booster Room 2 explosion, struck and became affixed to the bottom of the truck frame. With the truck's intermediate position facing south over the brow of the slope, the PETN blast caught the exposed portion of sheet metal protruding from behind the back dual and pushed it up and around the outside member of the truck frame. This siding could not end up in this position if the truck was facing Booster Room 2 as proposed by the comment.

A piece of mixing pot fragment lodged in the driver's side of the engine block. The radiator and other engine components were displaced toward the passenger side of the vehicle. This shows that the truck was facing east when struck by the blast from Booster Room 2 and could not be facing Booster Room 2 as the comment contends.

Another inconsistency in this comment is the assumption that if the Booster Room 2 blast occurred first, the truck would have rolled over when the PETN Building blast struck it. The physical evidence does not support this assumption. The chassis of the truck was resting on the brow of the slope when the PETN Building explosion occurred. In this configuration the truck had a lower center of gravity and consequently was not overturned by the blast. However, using the comment's conclusion, if the PETN Building exploded first, then the truck should have been rolled over by that blast, which was strong enough to destroy the concrete Boiler Building and roll a pickup truck onto its side.

Because the last movement of the flatbed truck was away from the PETN Building, the CSB concludes that the first explosion occurred in Booster Room 2.

6. **Comment:** All the damage to the pickup truck located south of the west door to Booster Room 1 was caused by the blast from the PETN building.

   CSB: The dishing depression of the door sustained by the pickup truck is characteristic of blast damage and could not have been caused by the mirror mounting hardware. The damage to it was caused by an over-pressurization condition. The blast effects of the Booster Room 2 explosion blew out all the reinforced, solid-grouted concrete-block walls of Booster Room 2, turned over the forklift located in the warehouse, blew the sliding panel door off of Booster Room 1, and caused the east wall of Booster Room 1 to collapse into the Booster Room. This massive release of energy was sufficient to cause the blast damage to the pickup truck parked outside Booster Room 1. Because a day's production of boosters (3000 to 4000 pounds of explosives) were either boxed or in bins on the south side of Booster Room 2, which shared a common wall with the restroom/shower area, explosion of this material had no substantial barrier to prevent blast damage to the west.

   The comment that pallets south of Booster Room 1 were not moved to the west is incorrect. Aerial photographs taken of the site after the explosions show pallets on the roadway west of their original position in addition to those that traveled northwest.

7. **Comment:** There was no heavy high trajectory debris from Booster Room 2 found near the PETN Building of the type required to penetrate the steel reinforced roof or the skylight, which had a grill of rebar on 8-inch centers to prevent unauthorized entry. The roof of Booster Room 2, composed of plywood, 2 x4 wood trusses, and sheet metal roofing, could not produce the necessary missile. However, the roof of the PETN building could produce a missile that could penetrate the Booster Room 2 roof and strike the PETN stored there.

CSB: The comment asserts that, “It is to be noted that no heavy trajectory type material was found between the PETN Building and Booster Room 2 nor was any recognizable material fitting this description found within a 200 foot radius of the PETN Building.” That there is relatively little material from the booster manufacturing buildings found immediately near the PETN crater supports the conclusion that the PETN Building must have exploded after Booster Room 2. There were large items from the general location of Booster Room 2 found within and beyond a 200-foot radius, however.

That there is very little material inside the PETN Building crater is easily explained if the PETN Building explosion occurred second. The PETN Building explosion left a forty-foot diameter crater in its former location; it knocked over the Boiler Building; it rolled the pickup truck on its side; and deposited pieces of the PETN Building and its contents over 2000 feet away. One of the steel-plate sides of the PETN magazine, which was originally located on the south side and adjacent to the PETN Building, was thrown approximately 160 feet to the east-south-east. A single piece of metal roofing found in the crater after the PETN Building explosion must have had a high trajectory, which kept it in the air beyond the 3.5 seconds between explosions.

There were ample materials in Booster Room 2, including metal struts, pipes, I-beams, shafts, mixer components, and pieces of the concrete wall that could have had the correct trajectory and be energetic enough to penetrate the PETN Building. Booster Room 2 materials were found within the perimeter of the original Booster Room 2. Materials were also found adjacent to Booster Room 2, and in trajectories that crossed or pointed toward the PETN Building. Mixing pot 6 was located within 20 feet of Booster Room 2 to the south. The pneumatic tank had a trajectory that carried it toward the PETN Building. Also, a stand from one of the work tables in Booster Room 2 landed approximately 160 feet beyond the PETN Building on a trajectory from Booster Room 2 that passed over the PETN Building. Because of the energy released during the explosion in the PETN Building, it is reasonable to assume that any large object hitting and detonating the PETN Building would not be found near the crater. This is further supported by the finding that there were no pieces of the PETN Building or magazine near the PETN crater. The overpressure from the explosion in Booster Room 2 would have destroyed the skylight over the east end of the PETN Building. Thus, hot or burning debris falling through this opening could also have initiated detonation of the PETN.

The comment has not disproved or provided convincing evidence to alter the CSB team’s conclusion that the explosion in the PETN Building was initiated by effects from Booster Room 2.

8. **Comment:** The presence of stainless steel fragments north of Booster Room 2, which came from pot 4, shows that the initial explosion did not occur in pot 5; it exploded sympathetically with other explosives in the room.

CSB: The comment states that “If the small amount of explosives (approximately 50 lbs. in pot 5) had been the initial explosion in Booster Room 2, the thin wall stainless steel small pot situated to the east and slightly south of pot 5 would not have contributed any fragment debris to the north.” This conclusion is unsupported by the physical evidence.

Pot parts, especially large pieces, were primarily found to the East, South, and West of Booster Room 2. None of the larger pieces, such as shafts, upper assemblies, or intact mixing pots were found to the north of Booster Room 2. Mixing pot leg brackets from large mixing pots and a portion of a mixing blade from a large pot, however, were found north of Booster Room 2. The chaos in Booster Room 2 during the explosion, other explosions in the room, or explosions from the PETN Building could have propelled smaller objects to their final locations to the north. It is not possible or necessary to determine all of the forces acting upon all the material at the site. That pot parts were found in virtually all directions demonstrates the chaotic nature of the explosion. Most of the stainless steel fragments found to the north were from the inner wall of large pots, which were thicker than the walls of the smaller pots.

9. **Comment:** The PETN ground level blast was concentrated in a narrow angle facing in a northwesterly direction. This rolled over the pickup truck in this zone, was witnessed by the worker boxing boosters in Booster Room 1, and propelled the witness against the west wall. The employee then heard a second explosion and the roof collapsed.

CSB: The blast sequence has been clearly established by the flatbed truck, layering, damage patterns, and other evidence. The observations and conclusions of individuals subjected to the explosion describing the conditions in the booster room are limited by their recollection of conditions that existed for milliseconds during the blasts. Perceptions of the direction of the blast are not valid given the conditions and the time for the boxer to observe the outside events from within the building out of the corner of his eye through a partially open sliding door. Given the setback of the truck from the edge of the slope, it is much more likely that the fireball seen by this worker originated from the explosion in the Booster Room 2 on the same level, than from the PETN Building 23 feet below the elevation of the witness and farther away.

The comment states the direction of ground blast effects were “narrowly concentrated” in a north-westerly direction. The blast was not focused. The PETN Building was located immediately south of a five-foot high riprapped slope leading up to the terrace below the production level. The PETN Building blast tore away a portion of the first berm on the north and deposited a fan of dirt on the next terrace and the riprapped slope to the production level. This gave the appearance of the blast being focused. In reality, the blast was essentially hemispheric, with blast effects in all directions.

Terracing and the pickup truck parked south of the PETN building’s open sliding door would have deflected the blast substantially. The line of sight from the center of the PETN crater to the open sliding door to Booster Room 1 was less than 20 degrees from being perpendicular to the south wall. Thus, the residual force would be directed more toward the north than toward the west wall where this witness landed.

There is independent corroboration that the first blast came from the east side of the room. The operator working beside the big pot in Booster Room 1 was thrown west across the room under the cooling bins toward the open door, rather than away from it.

The comment's discussion concerning the chevron pattern of the roof trusses in the warehouse supports the intensity of the blast emanating from Booster Room 2 but does not clarify explosion sequencing.

In the interviews of Booster Room 1 workers, no one ever described the piece of the roof of the Boiler Building coming through the south wall of Booster Room 1 just west of the loading dock. If the PETN Building detonated first, this would have occurred during the initial blast and would have been a significant event that the workers would have noticed.

Statements of the boxer in Booster Room 1 indicate that the first explosion threw him against the boxes stacked against the west wall, and caused the lights to fail and the roof to collapse. This sequence is confirmed in the interview he provided to the CSB. He then heard the second explosion, which was louder than the first, which is consistent with the larger quantity of PETN exploding after Booster Room 2. In another interview, of an operator in Booster Room 1, the operator stated that the roof collapsed after he heard the second explosion. This conflicts with the statements of Booster Room 1 workers interviewed by the CSB investigators.

10. **Comment:** When the windows were blown out of the backhoe in the gravel pit, the supervisor driving was stunned for a moment and then looked over his shoulder and saw the explosion of Booster Room 2 with the building "flying apart" and a black cloud over the main operating buildings. He indicated that the PETN Building exploded first followed by that of Booster Room 2.

CSB: The comment states that "This stunned [the supervisor] and after a moment he thought the shattering of the glass had been caused by a blowout of the large pneumatic tire behind him to the right." This assertion was directly contradicted during CSB's interview with the worker's supervisor. The Sierra legal representative was present when the supervisor stated clearly and unequivocally that the supervisor was not stunned and that he turned his head immediately to see what had happened. In spite of his conclusions, his description of the physical events does not support the PETN Building explosion being first. In fact, the supervisor never saw the PETN explosion. He assumed that the flash of light in the cab, the glass breakage, and blast he felt resulted from an explosion in the PETN Building.

11. **Comment:** In accordance with provisions from the DoD proposed rule (32 CFR Part 184), *Contractors' Safety for Ammunition and Explosives*, the protective construction provided in the design of the Sierra facilities serves as an alternative to the Institute of Makers of Explosives (IME) quantity-distance requirements. There are no quantity-distance requirements between working bays located in the same operating building since explosives were not transported from bay to bay. "Inhabited Building" separation distances are designed to protect the general public. Buildings occupied in connection with the manufacture, transportation, storage, or use of explosive materials are not considered to be "inhabited buildings" requiring this separation.

CSB: In this comment, the writer takes exception to the investigation team's observation that the IME quantity-distance recommendations were not met at the Kean Canyon facility. The response contends that the interpretation made by the investigation team is in error and provided a memorandum from an industry-hired investigator that states that " 'protective construction' is allowed in order to 'suppress explosion effects' as an alternate to distances that may be listed in the q[uantity] d[istance] table." It is unclear how this information, taken from a draft DoD standard, could apply to IME's guidance.

The industry-hired investigator's memorandum concludes that "Certainly the intent of 'Section 184.44 (c)' – to provide protection of personnel against death or serious injury against explosion communication between adjacent bays – can have no finer example than the design at Kean Canyon's operating building. All the employees in the first bay, Booster Room 1, were protected when the explosion occurred in the second bay, Booster Room 2."

The fatalities of the worker in the change room and the worker outside the flux manufacturing room, and the explosion in the PETN Building demonstrate that personnel and facilities adjacent or near to the booster manufacturing rooms were not protected. It is evident that the design did not effectively suppress explosion effects, as asserted by the memorandum. None of the construction at Kean Canyon could suppress the effects of several thousand pounds of explosives. Such a claim is ludicrous.

Section 3.2.16 of IME's Publication 3*, Suggested Code of Regulations for the Manufacture, Transportation, Storage, Sale, Possession and Use of Explosive Materials*, states in part:

"High explosive manufacturing buildings located on explosive materials plant sites . . . shall be separated by minimum distances conforming to the requirements of the 'Intra Plant Distance Table For Use Only Within Confines of Explosives Manufacturing Plants'."

Using the 20,000 pounds of explosives in Booster Room 1 and assuming that the terracing served as an effective barricade between facilities, the required minimum separation distance between the PETN Building and Booster Room 1 would have been 265 feet, rather than the actual separation of 185 feet. The comment may argue that Booster Rooms 1 and 2 were bays in the same building and Intraplant Quantity-Distance requirements don't apply between these bays. But if it is assumed that Booster Room 1 and 2 are explosive bays in the same building, the total quantity of explosives in the combined production buildings according to Sierra's own estimates would have been 32,000 pounds and the minimum distance from the production building to the PETN Building would be 295 feet.

The "DoD Ammunition and Explosives Safety Standard" siting requirements state: "Administration and industrial areas shall be separated from potential explosive sites by inhabited building distances." Because the minimum inhabited building distance is controlled by the fragment hazard distance of 1250 feet, the Frehner Construction Company gravel pit operations and the Sierra chemical operations did not meet this criteria.

12. **Comment:** The only credible scenario to explain how the first explosion occurred in the PETN building is sabotage in an attempt to cover up the theft of PETN. Several individuals could easily transport a large quantity of PETN from the site by backpack.

CSB: Having set out to show that the first explosion occurred in the PETN Building, the comment concludes that the explosion was the result of sabotage to mask the theft of a large quantity of PETN explosive. This was the only initiating event possible in this locked building that was unoccupied with no equipment in operation in the cold early morning of January 7, 1998. Because the PETN Building was locked, access would require insider assistance. Otherwise the missing lock and/or damaged door would have been clearly evident the following morning. In fact, the supervisor and workers present that morning drove past the door to the PETN Building and did not detect anything unusual the day of the incident. Setting off a delayed explosion to mask a theft and yet provide time to escape would require experience in the use of explosives and a timer to delay the ignition. The National BATF team members are trained to look for evidence of such devices, but found none. There was no indication that any of the workers other than the supervisor had ever detonated any explosives, and the supervisor's experience was limited to the testing of boosters. The gate into Sierra's Kean Canyon Plant was locked during off-hours and the Frehner Construction Company guard who monitored traffic into the site was located near that gate.

13. **Comment:** The CSB either misquoted or distorted testimony [interviews]. The CSB's investigators' statements that the operation was not controlled by any management system; that individuals were encourage to create processes that were efficient; that operators changed their processes as they liked; and that they did not require other outside reviews or independent oversight of those actions and might not even communicate to others what they were doing, are all evidence of this. Management felt it had strict control, consistent and frequent overview, and repetitive training to control the operation.

CSB: Multiple witness interviews support the conclusions made by the incident investigation team.

14. **Comment:** A double-axle trash trailer parked near the edge of the terrace south of Booster Room 2 and the Flux Room, was propelled into the wall of the flux room by the PETN explosion and then southeast by the explosion in Booster Room 2.

CSB: This evidence is not useful for establishing sequence. The trailer could have first been blown down to a lower terrace by the explosion in Booster Room 2 and then blow east by the explosion in the PETN Building. Alternately, the original location could have been further east than believed, such that the Booster Room 2 explosion blew the trailer components directly to their final resting points. The CSB investigators did not examine this issue because the preponderance of other evidence supported the CSB scenario.

15. **Comment:** A vertical metal wall panel from the south wall of the flux room has damage to the first 18 inches of the panel consisting of indentations and sandblasting while the top of the panel is shredded outwards. The damage at the bottom was caused by crushed rock south of the concrete apron being blown by the PETN explosion against the wall. The Booster Room 2 explosion then caused the shredding damage.

CSB: The CSB investigators did not examine this wall panel, but believes that there are other explanations that could account for such damage. The shredding of the wall panel was most likely caused by the blast from Booster Room 2; however, the damage to the lower portion of the panel could have been caused on impact or by its orientation to the effects of the second blast from the PETN Building explosion.

16. Comment: The roof of Booster Room 2 consisted of plywood covered by galvanized sheet metal panels, which were later covered by plywood and a fiberglass-asphalt top layer. Some galvanized sheet metal panels were found north of Booster Room 2 that show penetrations from both sides. Falling debris from the PETN explosion caused penetrations from one side followed by fragmentation from the Booster Room 2 explosion.

CSB: The CSB investigators did not examine this evidence. It is likely that all of this damage resulted from the blast in Booster Room 2, however. Some penetrations that appear to be from the top could have resulted from the sheet metal being blown away from roof trusses. Fasteners pulling through the sheet metal could give the appearance of a penetration from above. Due to the separation of explosives within the room and the generation of primary and secondary fragments, it is possible for the fragments from Booster Room 2 to have penetrated both sides of the roofing. Other penetrations could simply be due to the exposed panel being struck by falling metal fragments after the explosions.

17. Comment: An empty tank was strapped on a low-boy trailer east north east of the PETN Building on the same terrace. The PETN explosion struck the rear of the trailer and propelled it, and pieces of the tank along a line from the PETN building through the original location of the trailer. If Booster Room 2 had exploded first, the blast would have hit the side of the tank and propelled it south.

CSB: Because of the 80-foot setback of Booster Room 2 from the edge of the terrace to the south and the difference in elevations, the tank on the lowboy would not experience the direct impact of the blast that it would have experienced if it had been located on the same level. The trailer and tank were also partially shielded by a storage unit that was visible to the investigators. The tank was well secured to the trailer so the trailer itself kept the tank from being propelled south. Thus, this evidence was not seen as useful in establishing sequence.

EVIDENCE RELATED TO THE CSB'S INCIDENT SCENARIOS

The comments in response to the scenarios presented by the CSB investigators are presented below with the CSB's responses.

18. Comment: The use of sparking steel hammers or carpenters' hammers to break up explosives does not seem probable and was most likely a mistranslation of what was actually said. The supervisor stated that the use of steel hammers was strictly forbidden due to their spark potential. It appears, however, that workers, in violation of rules, occasionally used steel hammers and such use was quickly stopped.

CSB: There are multiple references in CSB interviews of Sierra employees to the use of steel hammers to break up lumps of Comp-B or reject boosters, and one employee's statements clarified the type of steel hammer they used as a carpenter's hammer. The scenario proposed by the CSB, however, had nothing to do with sparking. The detonation was due to "impact or impingement of explosives between the hammer and either a foreign object in the material or another hard surface." This result is possible whether the hammer was made of steel or a nonsparking material like bronze.

19. Comment: Turning on the agitator to pot 5 with solidified explosives present is not credible because the pots were left steam heated at night at a temperature of 180 degrees F, the operator who saw the residual explosives in this pot stated that the level was approximately 1 1/2 inches below the mixing blades, it was standard procedure to inspect the pots prior to activating the agitator, and the overload circuit protector was set to trip if the mix became too thick.

CSB: a) Cooling/solidification

The owner of Sierra stated that he asked the operators to leave one valve on each pot cracked open to ensure that the boiler would cycle to prevent freezing. He indicated from his observations that the temperature in the steam jacket would be 90-100 degrees. He confirmed that if explosives were left in the pot overnight, they would solidify. The morning of the incident was one of the coldest days that winter, which would further increase the likelihood that the explosives had solidified. Worker statements indicated that sometimes no valves were left cracked open.

It was standard practice for operators to shut off the valves and add flake TNT to bring the temperature of the mix down to get the proper viscosity. Because the operator who left explosives in his pot in Booster Room 2 may well have thought that his co-worker was going to use the remaining base mix, he could have left the steam valves to that kettle off in order to maintain the proper consistency. The co-worker indicated that typically, the Booster Room 2 operator who left explosives in his pot would leave the steam valve opened slightly to the draw-off line. The co-worker, however, did not check or open any valves on pot 5.

b) Mix Level

The co-worker told CSB investigators that the remaining base mix left in pot 5 was three to four inches deep and half-way up the hub at the base of the stirring blade. In the alternative scenario, it appears that this worker may have been stating that the level was 1 to 1 1/2 inches below the top of the stirring blade hub, which would be consistent with his earlier statements. The entire blade was not encased in solidified explosives. The mixing blades had only about one inch of clearance between the blade and the inner pot wall, as described in management interviews. Thus, the lowest portion of the blade extended into the solidified explosives.

CSB investigators also did an independent calculation using the inside diameter from drawings provided by Sierra to estimate the level based on the worker's estimate of quantity (one bucket full, about 50 pounds). The results were as follows:

2 inches	13.1 pounds
3 inches	28.8 pounds
4 inches	**50.3 pounds**
5 inches	77.0 pounds
6 inches	108.5 pounds

Thus, the worker statements we received concerning the amount of explosives left in pot 5 was supported by the calculation.

c) Failure to Inspect Pot

One operator working in Booster Room 2 did not feel the need to look inside his mixing pots every time. Another worker who had worked a few days in Booster Room 2 stated that he didn't think that the operator who left material in pot 5 normally looked into his pots before he turned the mixer on.

d) Spark/Pressure

The mixer used with the pots are capable of delivering over 4,000 inch pounds of torque (based on a manufacture's calculation dated January 30, 1998). This is more than enough torque energy to cause a detonation. The motor overloads in the mixers do not instantaneously drop out and were set at 8.5 to 9 amps (based on photographic evidence and manufacture's interpretation of the setting). Since only the lowest portion of the blade extended into the solidified explosives near the central mixing shaft, the explosives provided much less resistance to the torque of the mixing blade.

20. Comment: A spark from the mixing pot striking metallic debris in Comp-B is improbable because: 1) the operator would not have reached the point in the process in which Comp-B is poured into pot 5; 2) metal fragments were typically too small to be caught in the one-inch clearance between the agitator and pot wall; 3) Sierra had not had such an event over the past 25-year history using manual screening; and 4) the quality of reclaimed government explosives was improving.

CSB: The CSB scenario was misquoted by the comment. The actual scenario involved detonation of explosives by impact, friction, or shearing when foreign materials or hard lumps of Comp-B or substitute materials were added to the mixing pot. A bolt could easily be of sufficient size to be caught between the blade and the inner wall of the pot. Previously, the Comp-B pot in Booster Room 1 had sustained damage from foreign materials being caught between the mixing blade and the wall. The CSB investigators' timelines for each scenario were based on operators' accounts of the startup sequence. There was enough variation in this sequence that it is impossible to know exactly how the operator in Booster Room 2 was conducting his operation the morning of the incident. Sierra's manual screening process failed to eliminate foreign materials. This is clearly evident because most foreign materials were discovered in the pot after the pour.

21. Comment: Initiation by static electricity resulting from pouring dry PETN or drying PETN in the mixing pot is improbable. PETN was not dried in Pentolite pots before adding TNT, because this would cause clumping of the mixture, which would slow production. Also, the incident occurred before the operator would have reached this point in the operation.

CSB: The statements of the senior operator in Booster Room 2 clearly described the process of dry mixing of PETN to reduce residual moisture. When questioned further, he provided several assurances about putting the PETN in the pot without TNT. He did it all the time. This was the same operator responsible for training the other operators in Booster Room 2.

An operator normally would not begin with the Pentolite Pot. If the operator working the morning of the incident checked and saw the residual solidified base mix, however, he might have gone ahead and started the Pentolite mix while the base mix melted.

APPENDIX F: Visual and Metallographic Analysis of Mixer Parts

A visual examination of three items was performed. The items included:

- the hub portion of the cast mixing blade where the hub connected to the drive shaft of pot 5;
- a piece of the mixing blade believed to be from the same hub/mixing blade casting of pot 5; and
- an approximately 18-inch top section of the pot 5 shaft.

Following the visual analysis, sectioning and metallographic examinations were performed on portions of the hub and the mixing blade fragment.

Except for pot 5, the four large mixing pot shafts from Booster Room 2 remained intact following the blast. The three intact drive shafts still had the hub portion of the cast mixing blade firmly attached to the drive shafts. Because the shafts and hubs of all but pot 5 were accounted for, the remaining hub and the fractured portion of a shaft that were recovered at the site were determined to be those from pot 5.

The analysis found that the mixing blade hub was subjected to extreme shock loading as evidenced by shear bands and internal cracks. The mixing blade metallographic specimen showed the presence of mechanical twins that are an indication that the blade sections had been cold worked. Unlike the hub section, the blade fragment did not contain localized shear bands that are indicative of intense shock loading. From the limited metallographic study, the type of cold working that resulted in the mechanical twins observed in the blade fragment could not be determined.

Based upon the visual examination of the fracture surface of the drive shaft, the primary fracture mode could not be conclusively established. Further fractographic analysis using a scanning electron microscope would be expected to aid in establishing the fracture mode(s). Similarly, the visual examination of the fracture surface on the mixing blade fragment did not permit conclusive identification of the reason(s) for failure.

Interviews of Sierra workers indicated that 50 to 100 pounds of base mix was left in pot 5 at the end of the shift the day before the explosion. The metallurgical analysis concluded that the damage to the hub is consistent with shock loading that could result from contact with high explosive material upon detonation. This evidence strongly suggests that explosives were present in pot 5 when the explosion occurred.

The absence of shock loading on the piece of the mixing blade indicates that it was not in contact with explosives when the explosion occurred. One possible reason for the lack of shock loading is that the fragment may have been from a pot other than pot 5. Alternatively, the blade fragment may have been above the level of the 50-100 pounds of explosive remaining in the pot and thus experienced a less intense shock loading.

APPENDIX G: Melt/pour Incidents Elsewhere

The following table summarizes explosions that have occurred in melt/pour operations at other sites. These accounts indicate the degree of hazard associated with melt/pour operations and the types of initiating events that must be controlled. The source of this data is the U.S. Army and the IME.

Date	Event Description	Outcome	Location
7/24/16	Clogged draw-off pipe was being cleared with brass rod, which impinged heated Amatol (60/90) against steel pipe, causing detonation.	1 Fatality 3 Injuries	Trent, Great Britain
11/04/18	Foreign material was present in the melt pot due to lack of screening of fresh TNT or reworked Amatol. Approximately 1,200 lbs. of TNT was added to the pot from boxes without screening or examination. About 200 lbs. of scrap Amatol was added directly.	64 Fatalities 100 Injuries	Perth Amboy, New Jersey
12/12/41	Sublimed TNT crystals in ventilator duct due to high TNT vapor (0.87 mg/m^3) caused the explosion. Sublimed TNT crystals are sensitive to friction, impact, or static spark.	13 Fatalities 53 Injuries	Burlington, Iowa
3/4/42	Draw-off valves slamming shut were suspected in detonation of TNT (60-40 Amatol). Also, the exhaust-ventilation system was clogged by sublimation. The TNT vapor level was 0.80 mg/m^3.	22 Fatalities 84 Injuries	Burlington, Iowa
3/24/45	A hot-water hose with brass nozzle was being forced into a clogged draw-off pipe on a TNT melt unit. Impact or friction caused the explosion.	2 Fatalities	Joliet, Illinois
5/26/45	The agitator impacted a screen in a mixing pot or the valve diaphragm failed, resulting in metal-to-metal contact in TNT melt operation.	9 Fatalities 6 Injuries	Grand Island, Nebraska

Date	Event Description	Outcome	Location
10/01/51	Excess Comp-B detonated when warheads struck each other or fell to ground. Metal-to-metal contact of items coated with Comp-B caused the detonation.	5 Fatalities	Hawthorne, Nevada
2/20/59	Friction between a steel spatula and concrete floor contaminated with DNT-sublimated crystals caused a detonation.	1 Injury	Dottikon, Switzerland
7/6/61	Prolonged heating of 60 lbs. of molten Pentolite (55% PETN/45% TNT) led to detonation after seven hours. (Rotary valve was involved in explosion.)	Property damage	Seneca, Illinois
10/8/63	Cyclotol (70% RDX/30%TNT) detonation caused by impingement of explosives with spark-proof hammer and screwdriver while cleaning draw-off lines and valves.	2 Fatalities	Milan, Tennessee
8/16/68	Detonation of cyclotol melt operation probably caused by adding "riser scrap," which is explosive solidified in the risers used to fill projectiles and grenades, that normally is introduced into the melt pot when the molten explosive could bathe the scrap and soften it for re-melting. If riser scrap added prematurely, impact of the agitator could provide source of detonation. Evidence of detonation inside the melt pots was found.	6 Fatalities 4 Injuries	Shreveport, Louisiana
7/25/79	Decomposition of PETN during melting released oxides of nitrogen. Heat was removed but the reaction continued until detonation.	Property damage	East Camden, Arizona
8/18/89	A clogged draw-off line had been removed from a pot. Pentolite in the line detonated when struck by a non-sparking screwdriver with a rawhide mallet.	2 Fatalities	Joplin, Missouri

Scenario 1. The mixer blade impacted solidified explosives that had been left in pot 5 in Booster Room 2 the previous day.

Scenario 2. Foreign materials or hard lumps of Comp-B or substitute materials that were added to the base mix in pot 5 caused a detonation due to impact, friction, or shearing.

Scenario 3. Electrostatic discharge or friction detonated PETN that had been added to the Pentolite in pot 4 and allowed to heat up without any TNT in the pot to dissolve the PETN and act as a lubricant.

Scenario 4. The breaking of lumps of Comp-B or harder or more sensitive substitute materials with a steel hammer caused a detonation outside the mixing pot due to impact or impingement of explosives between hammer and a foreign object in the material or another hard surface.

Each of the changes identified in the Change Analysis Table had some influence on the melt/pour operation in Booster Room 2. This analysis shows that specific conditions that were present in the room when the incident occurred could have caused the detonation. The investigation team concluded that Scenario 1 is the most likely cause of this incident. This conclusion is based on the analysis of the number and types of changes as well as the probable human interaction with those changes.

The investigation team believes that these change factors support the conclusion that the melt/pour operator in Booster Room 2 did not verify the contents of mixing pot 5. He turned on the mixing element of pot 5 with 50 to 100 pounds of solid explosive material in it. This action resulted in the detonation of the material in the pot, which then propagated to the rest of Booster Room 2 and then to the PETN Building and magazine. The explosion resulted in the death of four workers and the injury of six others.

There is a strong case for the conclusion that Scenario 1 caused the explosion. It assumes, however, that the operator did not look into the pot before turning on the mixer. If the operator did look into the pot and did not turn on the mixer, then Scenarios 2, 3, or 4 could explain how the detonation occurred.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
1	Larger mixing pots were installed in Booster Room 2. The large mixing pots had an inside diameter of 46 inches. The smaller mixing pots in Booster Room 1 had diameters of less than or equal to 36 inches.	The larger pots had an inside radius of 23 inches, compared to an inside radius of 18 inches on the next-largest mixing pots used at the facility. This increased the surface area of the material left in the bottom of the larger pot. For the depth of material left in the pot, there was 27% more surface area. This would contribute to greater amounts of adhesion, crystal shearing, and rotational friction generated due to the mixing blade than from any previous configuration. This increased the likelihood of detonation due to friction, adhesion, or crystal shearing. It would also contribute to more rapid melting of material in the pot.	The larger capacity of the mixer allowed more material to be added during the initial steps of the process. Consequently, the operator could have added large amounts of the LX-14 and Comp-B to the pot. If this happened, then the material would be mixed in a dry configuration for several minutes before there was sufficient melting to reduce friction, eliminate impingement, or impact chunks of the explosive between the mixer blades and "breaker bars," or between the mixer blades and mixer walls. If foreign material was in the chunks, it could have caused additional friction or sparking until the material had melted.	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
2	The larger mixing pots in Booster Room 2 had “breaker bars.” These were not present in Booster Room 1.	Not Applicable	The “breaker bars” provided an additional component for the material to interact with during the mixing operation. If material were left in the bottom of mixing pot 5, then the working clearance between the “breaker bars” and the bottom of the mixer would be changed, possibly allowing impingement or impact to occur.	Not Applicable.	Not Applicable.
3	Wall thickness of larger mixing pots, including pot 5, compared to mixing pots used in Booster Room 1.	The heavier construction of the large mixing pots made them more rigid. Consequently, there would be little or no yielding when materials were forced between the mixing blades and walls of the pot. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	The heavier-walled pots were more rigid. As a result, there would be little or no yielding to materials between the mixing blades and walls. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	The heavier-walled pots were more rigid. Consequently, there would be little or no yielding to materials between the mixing blades and walls. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	Not Applicable.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
4	The steam system's heat capacity was greater than the hot-water system used in Booster Room 1.	The steam-heat system in Booster Room 2 had a higher heat capacity than the hot water system in Booster Room 1. The operators were able to melt material faster, and the pots had less buildup of material on the internal components. The operators were used to working with "clean" pots in Booster Room 2. They were less concerned about the internal condition of the pots than when they worked in Booster Room 1.	The higher heating capacity of the steam system in Booster Room 2 allowed the operators to add larger chunks of material to the pots.	PETN with a higher moisture content was brought to Booster Room 2 because it could be dried out without causing a significant delay in production. The practice for starting the Pentolite pot in Booster Room 2 was to put the PETN in the pot and allow it to mix without other materials while it dried out. This occurred while the melt/pour operators were doing the setup, which typically would take about 20 minutes.	With the higher heat capacity of the steam system, there was less need to break up some of the chunks of material being added to the pots. Workers were used to doing this operation, however, from their experience working in Booster Room 1.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
5	Normally, all material in the mixing pots was used up before the end of day shift. On this occasion, 50-100 lbs. of material was left in the pot at the end of the shift.	The material would harden overnight when the steam heat to the pot was reduced at the end of the shift. If the operator failed to look into the pot in the morning, he could have turned on the steam and then turned on the mixer with a large amount of solid explosive in the pot. This action could have resulted in a detonation due to crystal shearing, high friction in breaking the adhesion of the pot walls, or the friction of turning the material without any lubrication while the pot heated up.	The operator may have noticed that there was material in the pot. If he did, he would have waited about 10 minutes before adding the LX-14 or Comp-B to the mixer. On the surface, the pot contents may have looked liquid, but it is unlikely that the large mass of material would have been dissolved in this time frame. Adding chunks of material or material that could contain foreign objects in it could have provided a mechanism for detonation. The chunks may have been impacted or impinged during the mixing, friction in the dry mix may have been a detonation source, or metal objects in the mix could have been caught between the solid mass of residual mix and the bottom or sides of the mixing pot. All of these mechanisms may have been present.	If the operator noticed that pot 5 had a mass of material in the bottom, then he may have proceeded with the next step in his startup process, which would be to add PETN to the Pentolite pot 4.	If the operator recognized that there was material in the pot, he may then have decided to proceed with opening the LX-14 and Comp-B boxes. It was common practice at the facility to break up larger chunks of material using a steel hammer. This was done to reduce the time it takes for the material to melt. The process of breaking up the material included hitting the material in a shipping container, which could be located on the concrete floor or on another box of explosives. The operator may have been at this step of his process when the detonation occurred.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
6	PETN added to the mixing pot without TNT	Not Applicable	Not Applicable	In Booster Room 1, the PETN was added after some liquid TNT was added to the Pentolite-mixing pot. The TNT acted as a lubricant, and allowed the PETN to go into solution soon after being added. The electrostatic-discharge conditions described in the Environmental Changes section of this table would not be present if this step were followed in Booster Room 2.	Not Applicable.
7	Comp-B added to base-mix pot without first adding liquid or melting solid TNT	Not Applicable	The company's written procedure describing proper operation of the melt/pour process directed that the TNT be added before the Comp-B materials. This would have ensured that the Comp-B, which often was chunky and sometimes had metal foreign materials, would have some lubrication and fluid to help protect it from friction, impingement, and impacts during its melting. Adding the Comp-B first	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
			typically allowed a brief period of time when the material was still solid and thus susceptible to friction, impingement, or impact. If solid material left over from the previous evening were still in the pot, then it would increase the time of susceptibility.		
8	Single person operating the booster line instead of two people usually operating in Booster Room 2.	In Booster Room 1, two workers worked together in each production line. In Booster Room 2, only one person was operating each production line. This increased the number of tasks that needed to be performed, which increased the time pressures on the individual. This factor has a significant effect on human error. Time constraints affect decision processes and may influence individuals to take risks or act in unusual ways.	See explanation in Scenario 1 to the left.	Working by himself would increase the time between adding PETN and subsequently adding the TNT to the Pentolite pot.	See explanation in Scenario 1 to the left. Added time constraints and increased workload would have increased the likelihood of human error during the performance of this task.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
9	Hot water to the mixing pots was normally left on in Booster Room 1. In Booster Room 2, only one valve was left "cracked" open on the mixing pots overnight.	Workers in Booster Room 1 would not expect to find hard material in the bottom of a mixing pot, even if they left material in the pot overnight. This would tend to reduce the dependence on checking the pots because generally there would not be any solid material in the pots. Because the worker running the production line the morning of the incident learned his trade in Booster Room 1, the possibility that the material would be hard in the morning may not have occurred to him.	Not Applicable	Not Applicable	Not Applicable
	Material Change				
10	LX-14 material had larger and harder chunks	Not Applicable	See Scenario 2, Item 5, discussion. Increasing the size and hardness of chunks makes this situation worse.	Not Applicable	See Scenario 4, Item 5, discussion. Increasing the size and hardness of chunks makes this situation worse.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Operator Change				
11	The operator in Booster Room 2 had been trained and was experienced in operating in Booster Room 1 on the second shift. He had been working the day shift in Booster Room 2 for approximately 8 weeks.	The operator in Booster Room 2 had received on-the-job training for the melt/pour operation while working on the second shift in Booster Room 1. At the start of the second shift, the mixing pots would be mixing and already hot. In some instances, some material might have been left in them. Second-shift operators do not need to turn the mixer motor on; therefore, the operator in booster Room 2 may not have developed a habit of looking into the mixer before turning the mixer on. Even if the on-the-job training emphasized this precaution, the worker would not do it when working on the second shift in Booster Room 1.	Not Applicable	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Operator Change				
		Also, because it was a common practice to leave the pot empty at the end of the shift, failure to perform a precautionary look into the mixing pot would not normally be dangerous.			
12	The second operator was not working the morning of the incident.	The second operator knew that there was material left in pot 5. Had he been in the room, he may have reminded his coworker about the material left in the pot the previous evening.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.
	Environmental Change				
13	Low temperature outside (low to mid twenties), 81% relative humidity.	Booster Room 2 did not have a heater. The practice of leaving one of the valves on the pot cracked a small amount may have been enough to keep the material semi-liquid under certain conditions. In this instance, the quantity of material left in the pot combined with the cold	The cooler the material was in pot 5, the longer it would take to heat to liquid state. Adding material before the solid mass left in the pot had turned to liquid would have increased the likelihood of friction, impingement, or impact of materials.	Humidity drops by a factor of approximately one-half for every 20°F of temperature rise. Based on this property of temperature and humidity, as the temperature inside the pot was raised toward 200°F, the relative humidity in the pot would approach 0%. Low humidity, combined with the PETN granules and the	Not Applicable.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Environmental Change				
		outside temperature would contribute to the material being in solid form on the morning of the incident.		mixing action, would create ideal conditions for electrostatic discharges, which could result in detonation of the PETN.	